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SPATIAL ORIENTATION IN FLIGHT

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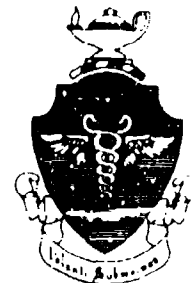
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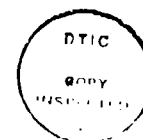
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<p>Man's orientational mechanisms, and how those mechanisms fail in flight, are discussed in detail in this comprehensive review. Specific topics include: mechanics and associated physiologic nomenclature; visual orientation; vestibular function and information processing; other senses of motion and position; spatial disorientation, including causes, types, examples, statistics, and methods of preventing spatial disorientation mishaps; and the significance, etiology, and therapy of motion sickness. Forty-three figures are included, many illustrating vestibular anatomy and physiology, and others depicting the more common visual and vestibular illusions in flight. Sixty-five classic references and a recommended reading list are also provided.</p>				
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SPATIAL ORIENTATION IN FLIGHT

MECHANICS

Operators of today's and tomorrow's air and space vehicles must understand clearly the terminology and physical principles relating to the motions of their craft so they can fly with precision and effectiveness. These crewmembers also have a working knowledge of the structure and function of the various mechanical and electrical systems of which their craft are comprised, to help them understand the performance limits of their machines, and to facilitate trouble-shooting and promote safe recovery when the machines fail in flight. So, too, must students of aerospace medicine understand certain basic definitions and laws of mechanics so they can analyze and describe the motional environment to which the flyer is exposed. In addition, the aeromedical professional must be familiar with the physiologic bases and operational limitations of the flyer's orientational mechanisms. This understanding is necessary to enable aeromedical professionals to speak intelligently and credibly with aircrew about spatial disorientation and to enable them to contribute significantly to investigations of aircraft mishaps in which spatial disorientation may be implicated.

Motion

There are only two types of physical motion: linear motion or motion of translation, and angular motion or motion of rotation. Linear motion can be further categorized as rectilinear, meaning motion in a straight line, or curvilinear, meaning motion in a curved path. Both linear motion and angular motion are composed of an infinite variety of subtypes, or motion parameters, based on successive derivatives of linear or angular position with respect to time. The most basic of these motion parameters, and the most useful, are displacement, velocity, acceleration, and jerk. Table 1 classifies linear and angular motion parameters and their symbols and units, and serves as an outline for the following discussions of linear and angular motion.

TABLE 1. LINEAR AND ANGULAR MOTION--SYMBOLS AND UNITS

Motion parameter	Linear		Angular	
	Symbols	Units	Symbols	Units
Displacement	x	meter (m) nautical mile (=1852 m)	θ	degree(deg) radian (rad) (=360/2 π deg)
Velocity	v, \dot{x}	meter/second (m/s) knot (=0.514 m/s)	$\omega, \dot{\theta}$	deg/s rad/s
Acceleration	a, \dot{v}, \ddot{x}	m/s ² g (=9.81 m/s ²)	$\alpha, \dot{\omega}, \ddot{\theta}$	deg/s ² rad/s ²
Jerk	j, $\dot{a}, \ddot{v}, \dddot{x}$	m/s ³ g/s	$\gamma, \dot{\alpha}, \ddot{\omega}, \ddot{\theta}$	deg/s ³ rad/s ³

Linear Motion. The basic parameter of linear motion is linear displacement. The other parameters--velocity, acceleration, jerk, etc.--are derived from the concept of displacement. Linear displacement, x, is the distance and direction of the object under consideration from some reference point; as such, it is a vector quantity, having both magnitude and direction. The position of an aircraft located at 25 nautical miles on the 150-degree radial of the San Antonio vortac, for example, describes the linear displacement of the aircraft from the navigational facility serving as the reference point. The meter (m), however, is the unit of linear displacement in the SI, or International System of Units, and will eventually replace other units of linear displacement such as feet, nautical miles, and statute miles. Often miles or feet must be converted into meters to facilitate calculations involving linear motion parameters. Thus, the aircraft in the above example is 25 nautical miles times 1.852×10^3 m/nautical mile, or 4.63×10^4 m, from San Antonio.

When linear displacement is changed during a period of time, another vector quantity, linear velocity, occurs. The formula for calculating the mean linear velocity, v, during time interval Δt is

$$v = \frac{x_2 - x_1}{\Delta t} \quad (1)$$

where

x_1 = initial linear displacement

and

x_2 = final linear displacement

An aircraft that travels from San Antonio to New Orleans in 1 hr, for example, moves with a mean linear velocity of 434 knots

(nautical miles per hour) on a true bearing of 086 degrees. Statute miles per hour and feet per second are other commonly used units of linear speed, the magnitude of linear velocity; but meters per second (m/s) is the SI unit, and is preferred. Frequently it is important to describe linear velocity at a particular instant in time, i.e., as Δt approaches zero. In this situation one speaks of instantaneous linear velocity, \dot{x} ("x-dot"), which is the first derivative of linear displacement with respect to time, $\frac{dx}{dt}$.

When the linear velocity of an object changes over time, the difference in velocity, divided by the time required for the moving object to make the change, gives its mean linear acceleration, a .

The formula
$$a = \frac{v_2 - v_1}{\Delta t} \quad (2)$$

where v_1 = initial velocity

v_2 = final velocity

and Δt = elapsed time

is used to calculate the mean linear acceleration, which, like displacement and velocity, is a vector quantity with magnitude and direction. Acceleration is thus the rate of change of velocity, just as velocity is the rate of change of displacement. The SI unit for the magnitude of linear acceleration is meters per second squared (m/s^2). Consider, for example, an aircraft which accelerates from a dead stop to a velocity of 100 m/s in 5 s; the mean linear acceleration is $(100 \text{ m/s} - 0 \text{ m/s}) \div 5 \text{ s}$, or 20 m/s^2 . The instantaneous linear acceleration, \ddot{x} ("x-double-dot") or \dot{v} , is the second derivative of displacement or the first derivative of velocity, $\frac{d^2x}{dt^2}$ or $\frac{dv}{dt}$, respectively.

A very useful unit of acceleration is g , which for our purposes is equal to the constant g_0 , the amount of acceleration exhibited by a freely falling body near the surface of the earth-- 9.81 m/s^2 . To convert values of linear acceleration given in m/s^2 into g units, simply divide by 9.81. In the above example in which an aircraft accelerates at a mean rate of 20 m/s^2 , 20 m/s^2 is divided by 9.81 m/s^2 per g to obtain an acceleration of 2.04 g .

A special type of linear acceleration, radial or centripetal acceleration, results in curvilinear, usually circular, motion. The acceleration acts along the line represented by the radius of the curve and is directed toward the center of curvature. Its effect is a continuous redirection of the linear velocity, in this case called tangential velocity, of the object subjected

to the acceleration. Examples of this type of linear acceleration occur when an aircraft pulls out of a dive after firing on a ground target, or engages an enemy in a circular path in aerial combat. The value of the centripetal acceleration, a_c , can be calculated if one knows the tangential velocity, v_t , and the radius, r , of the curved path followed:

$$a_c = \frac{v_t^2}{r} \quad (3)$$

As an example, we can calculate the centripetal acceleration of an aircraft traveling at 300 m/s (approximately 600 knots) and having a radius of turn of 1500 m. Dividing $(300 \text{ m/s})^2$ by 1500 m gives a value of 60 m/s^2 which when divided by 9.81 m/s^2 per g comes out to 6.12 g.

One can go another step in the derivation of linear motion parameters by obtaining the rate of change of acceleration. This quantity, j , is known as linear jerk. Mean linear jerk is calculated in the following way:

$$j = \frac{a_2 - a_1}{\Delta t} \quad (4)$$

where

a_1 = initial acceleration

a_2 = final acceleration

and

Δt = elapsed time

Instantaneous linear jerk, \ddot{x} or \dot{a} , is the third derivative of linear displacement or the first derivative of linear acceleration with respect to time; i.e., $\frac{d^3x}{dt^3}$ or $\frac{da}{dt}$, respectively.

Although the SI unit for jerk is m/s^3 , it is generally more useful to speak in terms of g-onset rate, measured in g's per second (g/s).

Angular Motion. The derivation of the parameters of angular motion follows in a parallel fashion the scheme used to derive the parameters of linear motion. The basic parameter of angular motion is angular displacement. For an object to be able to undergo angular displacement it must be polarized; i.e., it must have a front and back, so that it can face, or be pointed in, a particular direction. A simple example of angular displacement is seen in a person facing east, in which case his angular displacement is 90 degrees clockwise from the reference direction, north. Angular displacement, symbolized by θ , is generally measured in degrees, revolutions (1 rev = 360 deg), or radians (1 rad = 1 rev \div 2π , approximately 57.3 deg). The radian is a particularly convenient unit to use when dealing

with circular motion (e.g., motion of a centrifuge) because one needs only to multiply the angular displacement of the system, in radians, by the length of the radius to find the value of the linear displacement along the circular path. This relation holds because the radian is the angle subtended by a circular arc the same length as the radius of the circle.

Angular velocity, ω , is the rate of change of angular displacement. The mean angular velocity occurring in time interval Δt is calculated thus:

$$\omega = \frac{\theta_2 - \theta_1}{\Delta t} \quad (5)$$

where θ_1 = initial angular displacement

and θ_2 = final angular displacement

Instantaneous angular velocity is $\dot{\theta}$, or $\frac{d\theta}{dt}$. As an example of

angular velocity we can consider the standard-rate turn of instrument flying, in which a heading change of 180 degrees is made in 1 min. Then $\omega = (180 \text{ deg} - 0 \text{ deg}) \div 60 \text{ s}$, or 3 degrees per second (deg/s). This angular velocity can also be described as 0.5 revolutions per minute (rev/min, or rpm) or as 0.052 radians per second (rad/s) (3 deg/s divided by 57.3 deg per rad). The fact that an object may be undergoing curvilinear motion during a turn in no way affects the calculation of its angular velocity: an aircraft being rotated on the ground on a turntable at a rate of half a turn per minute has the same angular velocity as one flying a standard-rate instrument turn (3 deg/s) in the air at 300 knots.

Because radial or centripetal linear acceleration results when rotation is associated with a radius from the axis of rotation, a formula for calculating the centripetal acceleration, a_c , from the angular velocity, ω , and the radius, r , is often useful:

$$a_c = \omega^2 r \quad (6)$$

where ω is the angular velocity in radians per second. One can convert readily to the formula for centripetal acceleration in terms of tangential velocity (Eq. 3) if one remembers that

$$v_t = \omega r \quad (7)$$

To calculate the centripetal acceleration generated by a centrifuge having a 10-m arm and turning at 30 rpm, one uses Equation 6, after first converting 30 rpm to π radians per second. Squaring the angular velocity and multiplying by the 10-m radius, one obtains a centripetal acceleration of $10\pi^2 \text{ m/s}^2$, or 10.1 g.

The rate of change of angular velocity is angular acceleration, α . The mean angular acceleration is

$$\alpha = \frac{\omega_2 - \omega_1}{\Delta t} \quad (8)$$

where

ω_1 = initial angular velocity

ω_2 = final angular velocity

and

Δt = time interval over which angular velocity changes

$\ddot{\theta}$, $\dot{\omega}$, $\frac{d^2\theta}{dt^2}$, and $\frac{d\omega}{dt}$ can all be used to symbolize instantaneous angular acceleration, the second derivative of angular displacement or the first derivative of angular velocity with respect to time. If a figure skater is spinning at 6 revolutions per second (2160 deg/s, or 37.7 rad/s) and then comes to a complete stop in 2 s, the rate of change of angular velocity, or angular acceleration, is (0 rad/s - 37.7 rad/s) \div 2 s, or -18.9 radians per second squared. Angular acceleration cannot be expressed in g units, which measure magnitude of linear acceleration only.

Although not commonly used in aerospace medicine, another parameter derived from angular displacement is angular jerk, the rate of change of angular acceleration. Its description is completely analogous to that for linear jerk, but angular rather than linear symbols and units are used.

Force, Inertia, and Momentum

Linear and angular motions by themselves are of little physiologic importance. It is the forces and torques which result in, or appear to result from, linear and angular velocity changes that stimulate or compromise the crewmember's physiologic mechanisms.

Force and Torque. Force is an influence which produces or tends to produce linear motion or changes in linear motion; it is a pushing or pulling action. Torque produces or tends to produce angular motion or changes in angular motion; it is a twisting or turning action. The SI unit of force is the newton (N). Torque has dimensions of force and length, because torque is applied as a force at a certain distance from the center of rotation. The newton meter (N m) is the SI unit of torque.

Mass and Rotational Inertia. According to Newton's Law of Acceleration:

$$F = m a \quad (9)$$

where F = unbalanced force applied to an object

m = mass of the object

and a = linear acceleration

To describe the analogous situation pertaining to angular motion, we state that

$$M = j \alpha \quad (10)$$

where M = unbalanced torque (or moment) applied to the rotating object

j = rotational inertia (moment of inertia) of the object

and α = angular acceleration

The mass of an object is thus the ratio of the force acting on the object to the acceleration resulting from that force. Mass is therefore a measure of the inertia of an object--its resistance to being accelerated. Similarly, rotational inertia is the ratio of the torque acting on an object to the angular acceleration resulting from that torque--again, a measure of resistance to acceleration. The kilogram (kg) is the SI unit of mass, and is equivalent to $1 \text{ N}/(\text{m}/\text{s}^2)$. The SI unit of rotational inertia is merely the $\text{N m}/(\text{rad}/\text{s}^2)$.

Since $F = m a$, one can calculate the centripetal force, F_c , needed to produce a centripetal acceleration, a_c , of a mass, m :

$$F_c = m a_c \quad (11)$$

So from Equation 3
$$F_c = \frac{m v_t^2}{r} \quad (12)$$

or from Equation 6
$$F_c = m \omega^2 r \quad (13)$$

where v_t = tangential velocity

and ω = angular velocity

Newton's Law of Action and Reaction, that for every force applied to an object there is an equal and opposite reactive force exerted by that object, provides the basis for the concept of inertial force. Inertial force is an apparent force opposite in direction to an accelerating force and equal to the mass of the object times the acceleration. An aircraft exerting an accelerating forward thrust on its pilot causes an inertial force, the product of the pilot's mass and the acceleration, to be exerted on the back of the seat by the pilot's body. Similarly, an aircraft undergoing positive centripetal acceleration as a

result of lift generated in a turn causes the pilot's body to exert inertial force on the bottom of the seat. More important from our standpoint, however, are the inertial forces exerted on the pilot's blood and organs of equilibrium, as physiologic effects result directly from such forces.

At this point it is appropriate to introduce G , which is used to measure the strength of the gravitoinertial force environment. (Do not confuse G with G , the symbol for the universal gravitational constant, equal to $6.70 \times 10^{-11} \text{ N m}^2/\text{kg}^2$.) Strictly speaking, G is a measure of relative weight:

$$G = \frac{W}{W_0} \quad (14)$$

where

W = weight observed in the environment under consideration

and

W_0 = normal weight on the surface of the earth

In the physical definition of weight,

$$W = m a \quad (15)$$

and

$$W_0 = m g_0 \quad (16)$$

where

m = mass

a = acceleratory field (vector sum of actual linear acceleration plus an imaginary acceleration opposite the force of gravity)

and

g_0 = the standard value of the acceleration of gravity (9.81 m/s^2)

Thus, a man having a mass of 100 kg would weigh 100 kg times 9.81 m/s^2 or 981 N on earth (although conventional spring scales would read "100 kg"). At some other location or under some other acceleratory condition the same man could weigh twice as much--1,962 N--and cause a scale to read "200 kg." He would then be in a 2-G environment; or if he were in an aircraft, he would be "pulling" 2 G. Consider also that,

$$\begin{aligned} \text{since} \quad G &= \frac{W}{W_0} \\ &= \frac{m a}{m g_0} \end{aligned}$$

$$\text{then} \quad G = \frac{a}{g_0} \quad (17)$$

So we see that the ratio between the ambient acceleratory field (a) and the standard acceleration (g_0) can also be represented in terms of G.

Thus, we use g as a unit of acceleration (e.g., $a_c = 8 \text{ g}$), and reserve the dimensionless ratio of weights, G, for describing the resulting gravitoinertial force environment (e.g., a force of 8 G, or an 8-G load). When in the vicinity of the surface of the earth, one feels a G force equal to 1 G in magnitude directed toward the center of the earth. If one also sustains a G force resulting from linear acceleration, the magnitude and direction of the resultant gravitoinertial G force can be calculated by adding vectorially the 1-G gravitational force and the inertial G force. An aircraft pulling out of a dive with a centripetal acceleration of 3 g, for example, would exert 3 G of centrifugal force. At the bottom of the dive the pilot would experience the 3-G centrifugal force in line with the 1-G gravitational force, for a total of 4 G directed toward the floor of the aircraft. If the pilot could continue his circular flight path at a constant airspeed, the G force experienced at the top of the loop would be 2 G, since the 1-G gravitational force would subtract from the 3-G inertial force. Another common example of the addition of gravitational G force and inertial G force occurs during application of power on takeoff or on a missed approach. If the forward acceleration is 1 g, then the inertial force is 1 G directed toward the tail of the aircraft. The inertial force adds vectorially to the 1-G force of gravity, directed downward, to provide a resultant gravitoinertial force of 1.414 G pointing 45 degrees down from the aft direction.

Just as inertial forces oppose acceleratory forces, so do inertial torques oppose acceleratory torques. No convenient derived unit exists, however, for measuring inertial torque; specifically, there is no such thing as angular G.

Momentum. To complete this discussion of linear and angular motion, we introduce the concepts of momentum and impulse. Linear momentum is the product of mass and linear velocity, $m v$. Angular momentum is the product of rotational inertia and angular velocity, $j \omega$. Momentum is a quantity which a translating or rotating body conserves; i.e., an object cannot gain or lose momentum unless it is acted upon by a force or torque. A translational impulse is the product of force, F, and the time over which the force acts on an object, Δt , and is equal to the change in linear momentum imparted to the object. Thus

$$F \Delta t = m v_2 - m v_1 \quad (18)$$

where

v_1 = initial linear velocity

and

v_2 = final linear velocity

When dealing with angular motion, one defines a rotational impulse to be the product of torque, M , and the time over which it acts, Δt . A rotational impulse is equal to the change in angular momentum. Thus

$$M \Delta t = j \omega_2 - j \omega_1 \quad (19)$$

where

ω_1 = initial angular velocity

and

ω_2 = final angular velocity

The above relations can be seen to have been derived from the Law of Acceleration:

$$F = m a$$

$$M = j \alpha$$

since

$$a = \frac{v_2 - v_1}{\Delta t}$$

and

$$\alpha = \frac{\omega_2 - \omega_1}{\Delta t}$$

Directions of Action and Reaction

A number of conventions have been used in aerospace medicine to describe the directions of linear and angular displacement, velocity, and acceleration and of linear and angular reactive forces and torques. The more commonly used of those conventions will be described.

Vehicular Motions. Because space is three-dimensional, we describe linear motions in space by reference to three linear axes and angular motions by three angular axes. In aviation it is customary to speak of the longitudinal (fore-aft), lateral (right-left), and vertical (up-down) linear axes, and the roll, pitch, and yaw angular axes, as shown in Figure 1.

Most linear accelerations in aircraft occur in the vertical plane defined by the longitudinal and vertical axes, since thrust is usually developed along the former and lift is usually developed along the latter axis. Aircraft capable of vectored thrust are now operational, however, and vectored-lift aircraft are currently being flight tested. This means that in the relatively near future aircraft will operate in a complete, three-dimensional, linear acceleration environment. We can expect that spacecraft will do the same in the more distant future. Most angular accelerations in aircraft occur in the roll plane (perpendicular to the roll axis), and to a lesser extent in the pitch plane. Angular motion in the yaw plane is

very limited in normal flying, although it does occur during spins and several other aerobatic maneuvers. Again, aircraft and space vehicles of the future can be expected to operate with considerably more freedom of angular motion than those of the present.

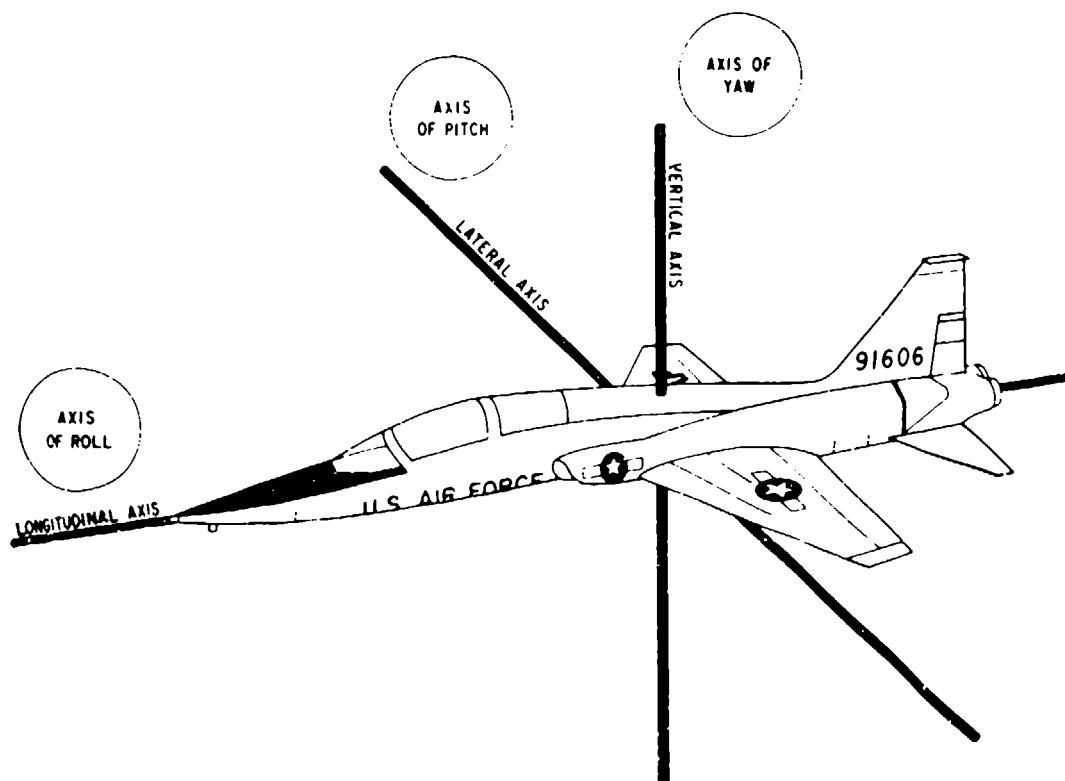


Figure 1. Axes of linear and angular aircraft motions. Linear motions are longitudinal, lateral, and vertical, and angular motions are roll, pitch, and yaw.

Physiologic Acceleration and Reaction Nomenclature. Figure 2 depicts a practical system for describing linear and angular accelerations acting on man. This system is used extensively in aeromedical scientific writing. In this system, a linear acceleration of the type associated with a conventional takeoff roll is in the $+a_x$ direction; i.e., it is a $+a_x$ acceleration. Braking to a stop during a landing roll results in $-a_x$ acceleration. Radial acceleration of the type usually developed during air combat maneuvering is $+a_z$ acceleration--foot-to-head. The right-hand rule for describing the relations between three orthogonal axes aids recall of the positive directions of a_x , a_y ,

and a_z accelerations in this particular system: if the forward-pointing index finger of the right hand represents the positive x-axis, and the left-pointing middle finger of the right hand represents the positive y-axis, then the positive z-axis is represented by the upward-pointing thumb of the right hand. Be aware, however, of a different right-hand rule used in another convention, one for describing vehicular coordinates. In that system, $+a_x$ is noseward acceleration, $+a_y$ is to the right, and $+a_z$ is floorward; an inverted right hand illustrates that set of axes.

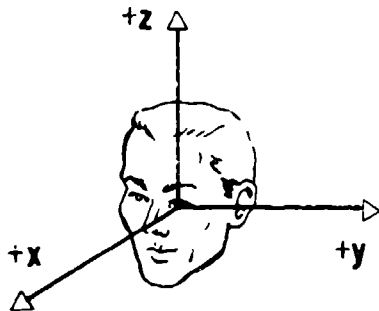
The angular accelerations, α_x , α_y , and α_z , are roll, pitch, and yaw accelerations, respectively, in the system shown in Figure 2. Note that the relation between the positive x-, y-, and z-axes is identical to that for linear accelerations. The direction of positive angular velocity or acceleration is described by another right-hand rule, wherein the flexed fingers of the right hand indicate the direction of angular motion corresponding to the vector represented by the extended, abducted right thumb. Thus, a right roll results from $+a_x$ acceleration, a pitch down results from $+a_y$ acceleration, and a left yaw results from $+a_z$ acceleration in this system. Again, be aware of the inverted right-hand coordinate system commonly used to describe angular motions of vehicles. In that convention a positive roll acceleration is to the right, positive pitch is upward, and positive yaw is to the right.

The nomenclature for the directions of gravitoinertial (G) forces acting on humans is also illustrated in Figure 2. Note that the relation of these axes to each other follows a backward, inverted, right-hand rule. In the illustrated convention, $+a_x$ acceleration results in $+G_x$ inertial force, and $+a_z$ results in $+G_z$. This correspondence of polarity is not achieved on the y-axis, however, as $+a_y$ acceleration results in $-G_y$ force. If the $+G_y$ direction were reversed, full polarity correspondence could be achieved between all linear accelerations and all reactive forces; and that convention has been used by some authors. An example of the usage of the symbolic reaction terminology would be: "An F-16 pilot must be able to sustain $+9.0 G_z$ without losing vision or consciousness."

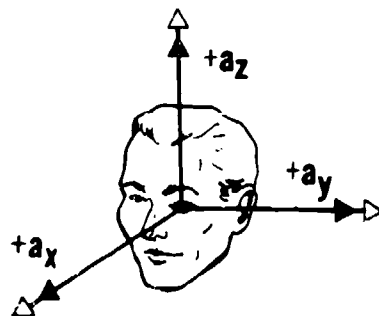


Figure 2. System for describing accelerations and inertial reactions in man. (Adapted from Hixson et al. (1).)

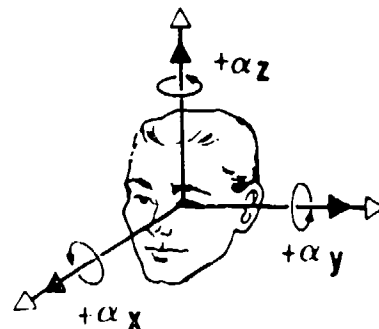
PHYSIOLOGICAL ACCELERATION NOMENCLATURE



ANATOMICAL AXES x, y, z

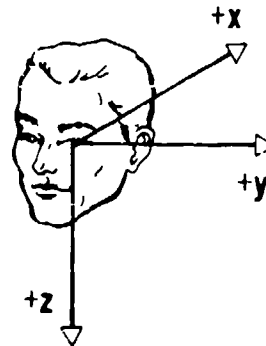


LINEAR ACCELERATION a_x, a_y, a_z

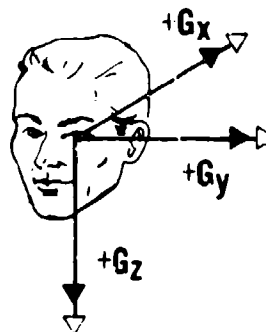


ANGULAR ACCELERATION $\alpha_x, \alpha_y, \alpha_z$

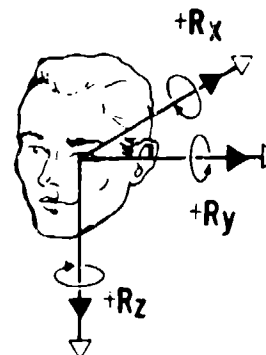
PHYSIOLOGICAL REACTION NOMENCLATURE



ANATOMICAL AXES x, y, z



LINEAR REACTION G_x, G_y, G_z



ANGULAR REACTION R_x, R_y, R_z

The "eyeballs" nomenclature is another very useful set of terms for describing gravitoinertial forces. In this system, the direction of the inertial reaction of the eyeballs when the head is subjected to an acceleration is used to describe the direction of the inertial force. The equivalent expressions, "eyeballs-in acceleration" and "eyeballs-in G force," leave little room for confusion about either the direction of the applied acceleratory field or the resulting gravitoinertial force environment.

Inertial torques can be described conveniently by means of the system shown in Figure 2, in which the angular reaction axes are the same as the linear reaction axes. The inertial reactive torque resulting from $+a_x$ (right roll) angular acceleration is $+R_x$, and $+a_z$ (left yaw) results in $+R_z$; but $+a_y$ (downward pitch) results in $-R_y$. This incomplete correspondence between acceleration and reaction coordinate polarities again results from the mathematical tradition of using right-handed coordinate systems.

It should be apparent that the potential for confusing the audience when speaking or writing about accelerations and inertial reactions is such as to make it a virtual necessity to describe the coordinate system being used. For most applications the "eyeballs" convention is perfectly adequate.

VISUAL ORIENTATION

Vision is by far the most important sensory modality subserving spatial orientation, especially so in moving vehicles such as aircraft. Without it, flight as we know it would be impossible, whereas this would not necessarily be the case in the absence of the vestibular or other sensory systems that provide orientation information. For the most part, the function of vision in spatial orientation is obvious--one sees where he is and how he is moving--so we shall not devote to it a discussion proportional in size to the importance of that function in orientation. Certain recent developments in our understanding of visual orientation deserve mention, however. First, the fact that there are actually two separate visual systems with two distinct functions--one being object recognition and the other spatial orientation--is of extreme importance, both for understanding visual illusions in flight and for appreciating the difficulties inherent in using flight instruments for spatial orientation. Second, the realization that visual and vestibular orientation information are integrated at very basic neural levels helps us understand why spatial disorientation so frequently is not amenable to correction by higher-level neural processing.

Anatomy of the Visual System

General. The retina, an evaginated portion of the embryonic brain, consists of an outer (more peripheral) layer of pigmented epithelium and an inner layer of neural tissue. Contained within the latter layer are the sensory rod and cone cells, the bipolar and horizontal cells that comprise the intraretinal afferent pathway from the rods and cones, and the multipolar ganglion cells, the axons of which are the fibers of the optic nerve. The cones, which number approximately seven million in the human eye, have a relatively high threshold to light energy. They are responsible for sharp visual discrimination and color vision. The rods, of which there are over a hundred million, are much more sensitive to light than are the cones; they provide the ability to see in twilight and at night. In the retinal macula, near the posterior pole of the eye, the cone population achieves its greatest density; within the macula, the fovea centralis--a small pit totally comprised of tightly packed slender cones--provides the sharpest visual acuity, and is the anatomic basis for foveal or central vision. The remainder of the eye is capable of far less visual acuity, and subserves paracentral and peripheral vision.

Having dendritic connections with the rods and cones, the bipolar cells provide axons that synapse with the dendrites or cell bodies of the multipolar ganglion cells, whose axons in

turn course parallel to the retinal surface and converge at the optic disc. Emerging from the eye as the optic nerve, they meet their counterparts from the opposite eye in the optic chiasm, and then continue in one of the optic tracts, most likely to terminate in a lateral geniculate body, but possibly in a superior colliculus or the pretectal area. Second-order neurons from the lateral geniculate body comprise the geniculocalcarine tract, which becomes the optic radiation and terminates in the primary visual cortex, the striate area of the occipital cerebral cortex (Area 17). In the visual cortex the retinal image is represented as a more or less point-to-point projection from the lateral geniculate body, which receives a similarly topographically structured projection from both retinas. The lateral geniculate body and the primary visual cortex are thus structurally and functionally suited for analysis of and recognition of visual images. The superior colliculi, on the other hand, project eventually to the motor nuclei of the extraocular muscles and muscles of the neck, and thus appear to provide a pathway for certain gross ocular reflexes of visual origin. Fibers entering the pretectal area are involved in pupillary reflexes. In addition, most anatomic and physiologic evidence indicates that information from the parietal cerebral cortex, the frontal eye movement area (Area 8), and the occipital visual association areas (Areas 18 and 19) is relayed through the paramedian pontine reticular formation to the nuclei of the cranial nerves (III, IV, and VI) innervating the extraocular muscles. Via this pathway and perhaps others involving the superior colliculi, saccadic (fast) and pursuit (slow) eye movements are initiated and controlled. Interestingly, saccadic eye movements appear to originate in the contralateral hemisphere, while pursuit movements are under ipsilateral cortical control (2).

Visual-vestibular Convergence. We now know that visually perceived motion information and probably other visual orientational data reach the vestibular nuclei in the brain stem (3,4). The neural pathways by which this convergence is accomplished are not known, however. The hypothesis that the superior colliculi project through the reticular formation to the vestibular nuclei is attractive, because of the demonstrated responsiveness of most superior colliculus neurons to moving rather than stationary visual stimuli; but this hypothesis is not yet supported by anatomic evidence. Most likely the cerebellum is involved in visual-vestibular convergence via the recently discovered accessory optic system. Visual information from the retina reaches the inferior olive by way of the accessory optic tract and central tegmental tract. Fibers from the inferior olive provide inputs to the Purkinje cells of the cerebellar flocculus, which have inhibitory connections in ipsilateral vestibular nuclei. Because this area of the cerebellum receives mossy fibers directly from vestibular end-organs, visual-vestibular interactions can also occur within the cerebellum; and as the Purkinje cells project onto the vestibular end-organs themselves (at least in some species), such

interactions can take place peripherally as well as centrally. There are also possible visual-vestibular interactions that occur as a result of cerebral cortical projections to the pontine nuclei, thence into the cerebellar vermis and cerebellar hemispheres. Of course, the confluence of visual and vestibular pathways in the paramedian pontine reticular formation makes possible the integration of visual and vestibular inputs to the final common pathway to the nuclei of cranial nerves III, IV, and VI. As we might expect, there are also afferent vestibular influences on visual system nuclei; and these have been demonstrated in the lateral geniculate body and superior colliculus (4).

Visual Information Processing

Primary control of man's ability to move and orient himself in three-dimensional space is mediated by the visual system. This is exemplified by the fact that individuals without functioning vestibular systems ("labyrinthine defectives") have virtually no problems with spatial orientation unless they are deprived of vision. The underlying mechanisms of visual orientation-information processing are revealed by receptive field studies, which have been accomplished for the peripheral retina, nuclear relays, and primary visual cortex. Basically, these studies show that there are several types of movement-detecting neurons, and that these neurons respond differently to the direction of movement, velocity of movement, size of the stimulus, its orientation in space, and the level of illumination. (For an excellent review of this fascinating topic, see Grüsser et al., 1973 (5).) Functionally, however, vision must be considered as two separate systems, one involved with object recognition and the other with spatial orientation. These two systems, the focal and ambient visual systems, respectively, will be described below, as will certain functions of yet another visual system, that responsible for generating eye movements to facilitate acquisition of orientation information.

Focal Vision. Liebowitz and Dichgans (6) have provided a very useful summary of the characteristics of focal vision:

"[The focal visual model] is concerned with object recognition and identification and in general answers the question of 'what.' Focal vision involves relatively fine detail (high spatial frequencies) and is correspondingly best represented in the central visual fields. Information processed by focal vision is ordinarily well represented in consciousness and is critically related to physical parameters such as stimulus energy and refractive error. The vast majority of studies in 'vision' as well as most

existing tests for evaluating performance or individual differences are concerned with focal function."

Focal vision is thus not primarily involved with orienting oneself in the environment, but is used in some instances to acquire visual information about orientation. Certainly, focal vision is necessary for reading flight instruments; however, a complex cognitive process--i.e., instrument flying skill--is required to convert such focally acquired orientation cues into usable orientation information.

In the visual (as opposed to instrument) flight environment, focal visual cues provide the primary means by which judgments of distance and depth are made. Tredici (7) categorizes these cues as being either monocular or binocular. The monocular cues are: (1) size constancy, the size of the retinal image in relation to known and comparative sizes of objects; (2) shape constancy, the shape of the retinal image in relation to the known shape of the object (e.g., the foreshortening of the image of a known circle into an ellipsoid shape means one part of the circle is farther away than another); (3) motion parallax, the relative speed of movement of images across the retina--when one is moving linearly in his environment, the retinal images of nearer objects move faster than those of objects farther away; (4) interposition, the partial obstruction from view of more distant objects by nearer ones; (5) texture or gradient, the apparent loss of detail with greater distance; (6) linear perspective, the convergence of parallel lines at a distance; (7) illumination perspective, which results from the tendency to perceive the light source to be above an object, and from the association of more deeply shaded parts of an object with being further from the light source; and (8) aerial perspective, the perception of objects to be more distant when the image is relatively bluish or hazy. The binocular cues to depth and distance are: (1) stereopsis, the visual appreciation of three-dimensional space that results from fusion of slightly dissimilar retinal images of an object; (2) vergence, the medial rotation of the eyes and the resulting direction of their gaze along more or less converging lines depending on whether the viewed object is closer or farther, respectively; and (3) accommodation, or focusing of the image by changing the curvature of the lens of the eye. Of all the cues listed, size and shape constancy and motion parallax appear to be most important for deriving distance information in flying, as they are available at and well beyond the distances at which binocular cues are useful. Stereopsis can provide orientation information at distances up to only about two hundred meters; it is, however, more important in orientation than are vergence and accommodation, which are of no use beyond about six meters.

Ambient Vision. Again, we refer to Liebowitz and Dichgans for a summary:

"[The ambient visual mode] subserves spatial localization and orientation and is in general concerned with the question of 'where.' Ambient vision is mediated by relatively large stimulus patterns so that it typically involves stimulation of the peripheral visual field and relatively coarse detail (low spatial frequencies). Unlike focal vision, ambient vision is not systematically related to either stimulus energy or optical image quality. Rather, provided the stimulus is visible, orientation responses appear to be elicited on an 'all or none' basis. ... The conscious concomitant of ambient stimulation is low or frequently completely absent. Interest in ambient visual function has a long history, but analyses of psychophysical properties, [etc.], ... have been initiated primarily within the past ten to fifteen years."

Ambient vision, therefore, is primarily involved with orienting oneself in the environment. Furthermore, this function is completely independent of the function of focal vision. This is evidenced by the fact that one can fully occupy central vision with the task of reading while simultaneously obtaining sufficient orientation cues with peripheral vision to walk or ride a bicycle. It is also evidenced by the ability of certain patients with cerebral cortical lesions to maintain visual orientation responses even though their ability to discriminate objects is lost ("blindsight"--presumably mediated through subcortical structures).

The function of ambient vision in orientation can be thought of as two processes, one providing motion cues and the other providing position cues. Large, coherently moving contrasts detected mainly with peripheral vision result in a percept of self-motion, or vection. If the moving contrasts revolve relative to the subject, he perceives rotational self-motion, or angular vection, which can be in the pitch, roll, yaw, or any intermediate plane. If the moving contrasts enlarge and diverge from a distant point, become smaller and converge in the distance, or otherwise indicate linear motion, the percept of self-motion that results is linear vection, which also can be in any direction. Vection can, of course, be veridical or illusory, depending on whether actual or merely apparent motion of the subject is occurring. One can appreciate the importance of ambient vision in orientation by recalling the powerful sensations of self-motion generated by certain scenes in wide-screen motion pictures (e.g., flying through the Grand Canyon).

Position cues provided by ambient vision are readily evidenced in the stabilization of posture that vision affords patients with defective vestibular or spinal proprioceptive systems. The essential visual parameter contributing to postural stability appears to be motion of the retinal image that results from minor deviations from desired postural position. Visual effects on posture can also be seen in the phenomenon of height vertigo. As the distance from (height above) a stable visual environment increases, the amount of body sway necessary for the retinal image movement to be above threshold increases. Above a certain height the ability of this visual mechanism to contribute to postural stability is exceeded, and vision indicates posture to be stable despite large body sways. The conflict between visual orientation information, indicating relative stability, and the vestibular and somatosensory data, indicating large body sways, results in the unsettling experience of vertigo.

One more distinction between focal and ambient visual function should be emphasized. In general, focal vision serves to orient the perceived object relative to oneself, whereas ambient vision serves to orient oneself relative to the perceived environment. When both focal and ambient vision are present, orienting a focally perceived object relative to the ambient visual environment is easy, whether the mechanism employed involves first orienting the object to oneself and then orienting oneself and the object to the environment, or whether the object is oriented directly to the environment. When only focal vision is available, however, it can be difficult to orient oneself correctly to a focally perceived orientation cue, because the natural tendency is to perceive oneself as stable and upright, and to perceive the focally viewed object as oriented otherwise with respect to the stable and upright egocentric reference frame. This phenomenon can cause a pilot to misjudge his approach to a night landing, for example, when only the runway lights and a few other focal visual cues are available for spatial orientation.

Eye Movements. The maintenance of visual orientation in a dynamic environment is greatly enhanced by the ability to move the eyes, primarily because the retinal image of a moving object or environment can be stabilized by appropriate eye movements. Very basic and powerful mechanisms involved in reflexive vestibular stabilization of the retinal image will be discussed in the section on vestibular function. Visually controlled eye movements that provide image stabilization are the slow pursuit movements and the rapid saccadic movements. Pursuit movements adequately track targets moving at less than 60 degrees/s; targets moving at higher velocities necessitate either saccadic eye movements or voluntary head movements for adequate tracking. Saccadic eye movements are used voluntarily or reflexively to acquire a target or to catch up to a target which cannot be maintained on the fovea by pursuit movements. Under some circumstances, pursuit and saccadic eye movements alternate in a

pattern of reflexive slow tracking and fast back-tracking--optokinetic nystagmus. This type of eye-movement response is typically elicited in the laboratory by surrounding the subject with a rotating striped drum; but one can exhibit and experience optokinetic nystagmus quite readily in a more natural setting by watching railroad cars go by while waiting at a railroad crossing. Movement of the visual environment sufficient to elicit optokinetic nystagmus provides a stimulus that can either enhance or compete with vestibular elicitation of eye movements, depending on whether the visually perceived motion is compatible or incompatible, respectively, with that sensed by the vestibular system. Vergence movements, which aid binocular distance and motion perception at very close range, are also visually controlled, but are of relatively minor importance in spatial orientation when compared with the image-stabilizing pursuit and saccadic eye movements.

Even though gross stabilization of the retinal image aids object recognition and spatial orientation by enhancing visual acuity, absolute stability of an image is associated with a marked decrease in visual acuity and form perception, as shown experimentally by Ditchburn and Ginsborg (8). This stability-induced decrement is avoided by continual voluntary and involuntary movements of the eyes, even during fixation of an object. We are unaware of these small eye movements, however, and the visual world appears stable.

We tend to take for granted that voluntary scanning and tracking movements of the eyes are associated with the appearance of a stable visual environment; but why this is so is not readily apparent. Early investigators postulated that proprioceptive information from the extraocular muscles provided not only feedback signals for control of eye movements but also the afferent information needed to correlate eye movement with retinal image movement and arrive at a subjective determination of a stable visual environment. In 1960 Brindley and Merton (9) demonstrated that in man there is no subjective eye-position sense--i.e., no conscious extraocular-muscle proprioception. An alternative mechanism for oculomotor control and subjective appreciation of visual stability then became plausible: that was the "corollary discharge" or feed-forward mechanism first proposed by Sperry (10). From his studies of the motor effects of surgical rotation of the eye in fish, Sperry concluded: "Thus, an excitation pattern that normally results in a movement that will cause a displacement of the visual image on the retina may have a corollary discharge into the visual centers to compensate for the retinal displacement. This implies an anticipatory adjustment in the visual centers specific for each movement with regard to its direction and speed." The theoretical aspects of visual perception of movement and stability have been expanded over the years into various models based on "inflow" (afference), "outflow" (efference), and even hybrid sensory mechanisms. The interested reader will enjoy Cohen's (11) concise discussion of these models as they relate to spatial orientation.

VESTIBULAR FUNCTION

The role of vestibular function in spatial orientation is not so overt as that of vision, but is extremely important for three major reasons. First, the vestibular system provides the structural and functional substrate for reflexes that serve to stabilize vision when motion of the head and body would otherwise result in blurring of the retinal image. Second, the vestibular system provides orientational information with reference to which both skilled and reflexive motor activities are automatically executed. Third, the vestibular system provides, in the absence of vision, a reasonably accurate percept of motion and position, as long as the pattern of stimulation remains within certain naturally occurring bounds. Because the details of vestibular anatomy and physiology are not usually well known by medical professionals, and because a working knowledge of them is essential to the understanding of spatial disorientation in flight, we present those details here.

Vestibular Anatomy

End-organs. The vestibular end-organs are smaller than most people realize: measuring just 1.5 cm across, the whole vestibular sensory apparatus would fit inside the bowl of a typical pipe. They reside well-protected within some of the densest bone in the body, the petrous portion of the temporal bone. Each temporal bone contains a tortuous excavation known as the bony labyrinth, which is filled with perilymph, a fluid much like cerebrospinal fluid in composition. The bony labyrinth consists of three main parts: the cochlea, the vestibule, and the semicircular canals (Fig. 3). Within each part of the bony labyrinth is a part of the delicate, tubular, membranous labyrinth, which contains endolymph, a fluid characterized by its relatively high concentration of potassium. In the cochlea the membranous labyrinth is called the cochlear duct or scala media; this organ converts acoustic energy into neural information. In the vestibule lie the two otolith organs, the utricle and the sacculus. They translate gravitational and inertial forces into spatial orientation information--specifically, information about position and linear motion of the head. The semicircular ducts, contained in the semicircular canals, convert inertial torques into information about angular motion of the head. The three semicircular canals and their included semicircular ducts are oriented in three mutually perpendicular planes, thus inspiring the names of the canals: anterior vertical (or superior), posterior vertical (or posterior), and horizontal (or lateral).

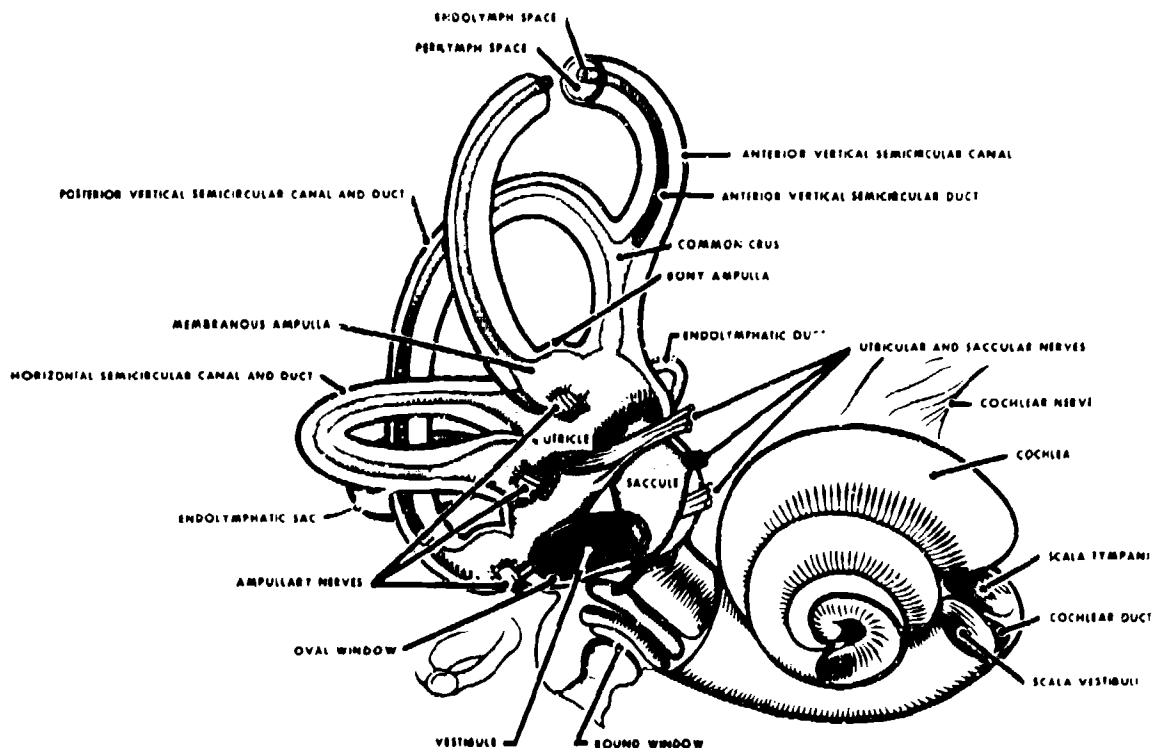


Figure 3. Gross anatomy of the inner ear. The bony semicircular canals and vestibule contain the membranous semicircular ducts and otolith organs, respectively.

The semicircular ducts communicate at both ends with the utricle, and one end of each duct is dilated to form an ampulla. Inside each ampulla lies a crest of neuroepithelium, the crista ampullaris; atop the crista, occluding the duct, is a gelatinous structure called the cupula (Fig. 4a). The hair cells of which the crista ampullaris is composed project their cilia into the base of the cupula, so that whenever the cupula moves, the cilia are bent.

Lining the bottom of the utricle in a more or less horizontal plane is another patch of neuroepithelium, the macula utriculi; and on the medial wall of the saccule in a vertical plane is still another, the macula sacculi (Fig. 4b). The cilia of the hair cells comprising these structures project into overlying otolithic membranes, one above each macula. The otolithic membranes are gelatinous structures containing many tiny calcium carbonate crystals, called otoconia, which are held together by a network of connective tissue. Having almost three times the density of the surrounding endolymph, the otolithic membranes displace endolymph and shift position relative to

their respective maculae when subjected to changing gravito-inertial forces. This shifting of otolithic membrane position results in bending of the cilia of the macular hair cells.

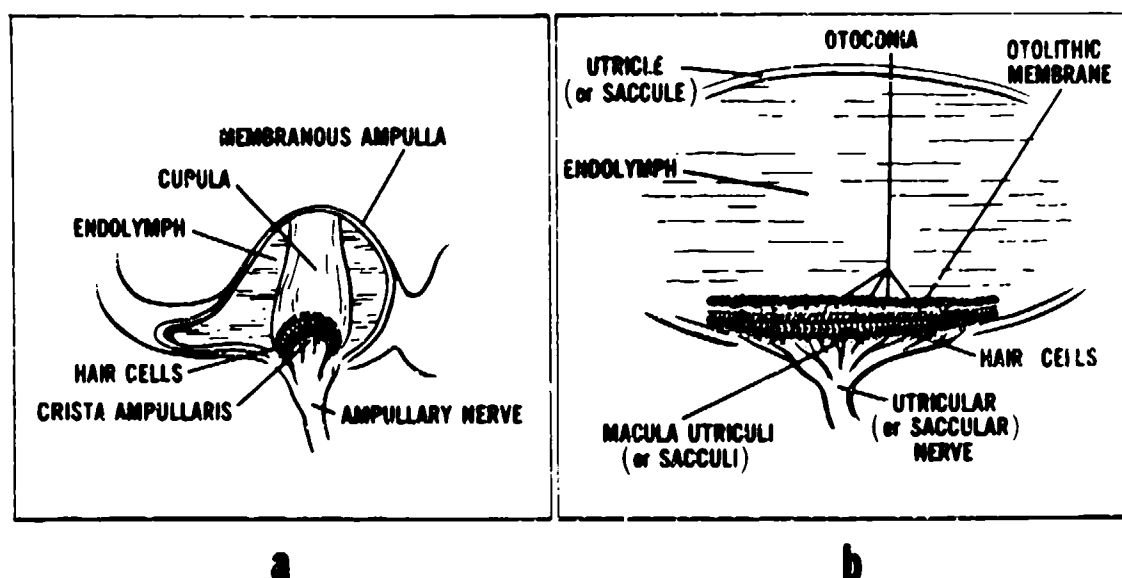


Figure 4. The vestibular end-organs. a. The ampulla of a semi-circular duct, containing the crista ampullaris and cupula. b. A representative otolith organ, with its macula and otolithic membrane.

The hair cell is the functional unit of the vestibular sensory system: it converts spatial and temporal patterns of mechanical energy applied to the head into neural information. Each hair cell possesses one relatively large kinocilium on one side of the top of the cell and up to a hundred smaller stereocilia on the same surface. Hair cells thus exhibit morphologic polarization; i.e., they are oriented in a particular direction. The functional correlate of this polarization is that when the cilia of a hair cell are bent in the direction of its kinocilium, the cell undergoes an electrical depolarization, and the frequency of action potentials generated in the vestibular neuron attached to the hair cell increases above a certain resting frequency--the greater the deviation of the cilia, the higher the frequency. Similarly, when its cilia are bent away from the side with the kinocilium, the hair cell undergoes an electrical hyperpolarization, and the frequency of action potentials in the corresponding neuron in the vestibular nerve decreases (Fig. 5).

POSITION OF CILIA	NEUTRAL	TOWARD KINOCILIUM	AWAY FROM KINOCILIUM
KINOCILIUM (1) STEREOCILIA (60 - 100) HAIR CELL VESTIBULAR AFFERENT NERVE ENDING ACTION POTENTIALS VESTIBULAR EFFERENT NERVE ENDING			
POLARIZATION OF HAIR CELL	NORMAL	DEPOLARIZED	HYPERPOLARIZED
FREQUENCY OF ACTION POTENTIALS	RESTING	HIGHER	LOWER

Figure 5. Function of a vestibular hair cell. When mechanical forces deviate the cilia toward the side of the cell with the kinocilium, the hair cell depolarizes and the frequency of action potentials in the associated afferent vestibular neuron increases. When the cilia are deviated in the opposite direction, the hair cell hyperpolarizes and the frequency of action potentials decreases.

The same basic process described above occurs in all the hair cells in the three cristae and both maculae; the important differences lie in the physical events that cause the deviation of cilia and in the directions the various groups of hair cells are oriented. The hair cells of a crista ampullaris respond to the inertial torque of the ring of endolymph contained in the attached semicircular duct, as the reacting endolymph exerts pressure on the cupula and deviates it. The hair cells of a macula, on the other hand, respond to the gravito-inertial force acting to displace the overlying otolithic membrane. As indicated in Figure 6a, all of the hair cells in the crista of the horizontal semicircular duct are oriented so that their kinocilia are on the utricular side of the ampulla. Thus, utriculopetal endolymphatic pressure on the cupula deviates the cilia of these hair cells toward the kinocilia, and all the hair cells in the

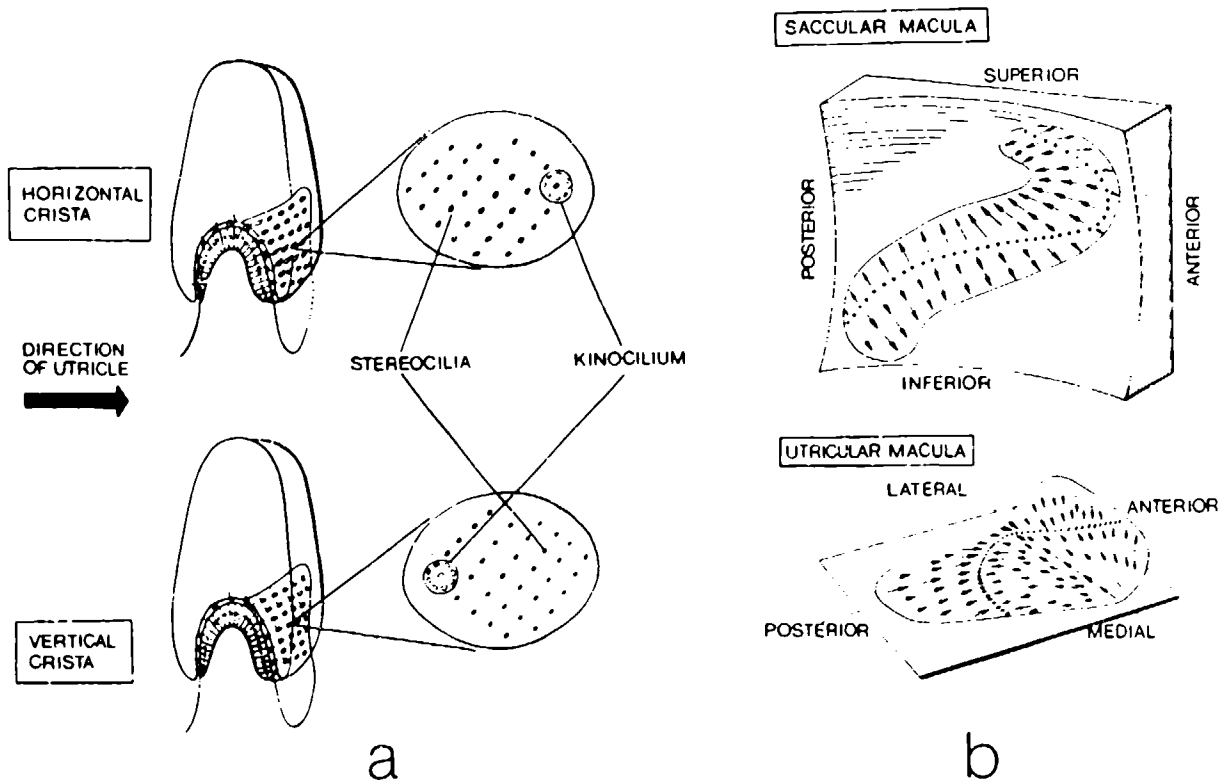


Figure 6. Morphologic polarization in vestibular neuroepithelia. a. All the hair cells in the cristae of the horizontal semicircular ducts are oriented so that their kinocilia are in the direction of the utricle; those in the cristae of the vertical ducts have their kinocilia directed away from the utricle. b. The maculae of the saccule (above) and utricle (below) also exhibit polarization--the arrows indicate the direction of the kinocilia of the hair cells in the various regions of the maculae. (Adapted from Spoendlin (12).)

crista depolarize. The hair cells in the cristae of the vertical semicircular ducts are oriented in the opposite fashion; i.e., their kinocilia are all on the side away from the utricle. In the ampullae of the vertical semicircular ducts, therefore, utriculopetal endolymphatic pressure deviates the cilia away from the kinocilia, causing all the hair cells in these cristae to hyperpolarize. In contrast, the hair cells of the maculae are not oriented unidirectionally across the neuroepithelium: the direction of their morphologic polarization depends on where they lie on the macula (Fig. 6b). In both maculae there is a central line of reflection, on opposing sides of which the hair cells assume an opposite orientation. In the utricular macula the kinocilia of the hair cells are all oriented toward this line of reflection, whereas in the saccular macula they are oriented away from it. Because the line of reflection on each macula curves at least ninety degrees, the hair cells, having

morphologic polarization roughly perpendicular to this line, exhibit virtually all possible orientations on the plane of the macula. Thus, the orthogonality of the planes of the three semicircular ducts enables them to detect angular motion in any plane; and the perpendicularity of the planes of the maculae, plus the omnidirectionality of the orientation of the hair cells in the maculae, allow the detection of gravito-inertial forces acting in any direction.

Neural Pathways. To help the student organize better in his mind, the potentially confusing vestibular neuroanatomy, a somewhat simplified overview of the major neural connections of the vestibular system is presented in Figure 7. The utricle nerve, two sacculus nerves, and the three ampullary nerves converge to form the vestibular nerve, a portion of the VIIIth cranial or statoacoustic nerve. Within the vestibular nerve lies the vestibular (or Scarpa's) ganglion, which is comprised of the cell bodies of the vestibular neurons. The dendrites of these bipolar neurons invest the hair cells of the cristae and maculae; most of their axons terminate in the four vestibular nuclei in the brain stem--the superior, medial, lateral, and inferior--but some enter the phylogenetically ancient parts of the cerebellum to terminate in the fastigial nuclei and in the cortex of the flocculonodular lobe and other parts of the posterior vermis.

The vestibular nuclei project via secondary vestibular tracts to the motor nuclei of the cranial and spinal nerves and to the cerebellum. As vestibulo-ocular reflexes are a major function of the vestibular system, it is not surprising to find ample projections from the vestibular nuclei to the nuclei of the oculomotor, trochlear, and abducens nerves (cranial nerves III, IV, and VI, respectively). The major pathway of these projections is the ascending medial longitudinal fasciculus (MLF). The basic vestibulo-ocular reflex is thus served by sensor and effector cells and an intercalated three-neuron reflex arc from the vestibular ganglion to the vestibular nuclei to the nuclei innervating the extraocular muscles. In addition, there are indirect multisynaptic pathways that course from the vestibular nuclei through the paramedian pontine reticular formation to the oculomotor and other nuclei. The principle of ipsilateral facilitation and contralateral inhibition via an interneuron very clearly operates in vestibulo-ocular reflexes, and numerous crossed internuclear connections provide evidence of this. The vestibulo-ocular reflexes that the various ascending and crossed pathways support serve to stabilize the retinal image by moving the eyes in the direction opposite that of the motion of the head. Via the descending MLF and medial vestibulo-spinal tract, crossed and uncrossed projections from the vestibular nuclei reach the nuclei of the spinal accessory nerve (cranial nerve XI) and motor nuclei in the cervical cord. These projections form the anatomic substrate for vestibulocollic reflexes, which serve to stabilize the head by appropriate action of the sternocleidomastoid and other neck muscles. A

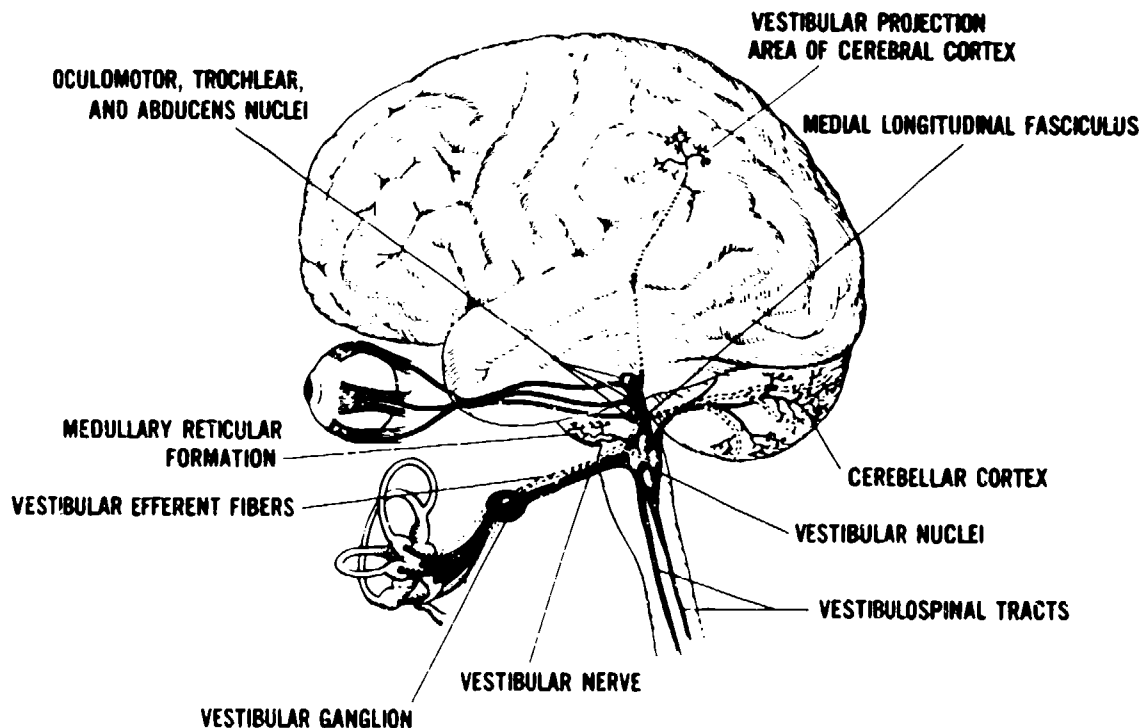


Figure 7. Major connections and projections of the vestibular system.

third projection is that from primarily the lateral vestibular nucleus into the ventral gray throughout the length of the spinal cord. This important pathway is the uncrossed lateral vestibulospinal tract, which enables the vestibulospinal (pos-tural) reflexes to help stabilize the body with respect to an inertial frame of reference by means of sustained and transient vestibular influences on basic spinal reflexes. Secondary vestibulocerebellar fibers course from the vestibular nuclei into the ipsilateral and contralateral fastigial nuclei and to the cerebellar cortex of the flocculonodular lobe and elsewhere. Returning from the fastigial and other cerebellar nuclei, crossed and uncrossed fibers of the cerebellobulbar tract terminate in the vestibular nuclei and in the associated reticular formation. There are also efferent fibers from the cerebellum, probably arising in the cerebellar cortex, which terminate not in nuclear structures, but on dendritic endings of primary vestibular afferent neurons in the vestibular neuroepithelia. Such fibers are those of the vestibular efferent system, which appears to modulate or control the information arising from the vestibular end-organs. The primary and secondary vestibulocerebellar fibers and those returning from the cerebellum to the vestibular area of the brainstem comprise the juxtarestiform body of the inferior cerebellar peduncle. This structure, along with the vestibular end-organs, nuclei, and projection areas in

the cerebellum, collectively constitute the so-called vestibulo-cerebellar axis, the neural complex responsible for processing primary spatial orientation information and initiating adaptive and protective behavior based on that information.

Several additional projections, more obvious functionally than anatomically, are those to certain autonomic nuclei of the brain stem and to the cerebral cortex. The dorsal motor nucleus of cranial nerve X (vagus) and other autonomic cell groups in the medulla and pons receive secondary vestibular fibers, largely from the medial vestibular nucleus; these fibers mediate vestibulovegetative reflexes manifesting as the pallor, perspiration, nausea, and vomiting--motion sickness--that can result from excessive or otherwise abnormal vestibular stimulation. Via vestibulothalamic and thalamocortical pathways, vestibular information eventually reaches the primary vestibular projection area of the cerebral cortex, currently thought to be located in the parietal or parietoinsular cortex (not in the temporal lobe, as previously suspected). This projection area is provided with vestibular, visual, and somatosensory proprioceptive representation, and is evidently associated with conscious spatial orientation and integration of sensory correlates of higher-order motor activity. In addition, vestibular information can be transmitted via long polysynaptic pathways through the brainstem reticular formation and medial thalamus to wide areas of the cerebral cortex; the nonspecific cortical responses to vestibular stimuli that are evoked via this pathway appear to be associated with an arousal or alerting mechanism.

Vestibular Information Processing

As the reader should have deduced from the discussion of the anatomy of the vestibular end-organs, angular accelerations are the adequate, i.e., physiologic, stimuli for the semicircular ducts, and linear accelerations and gravity are the adequate stimuli for the otolith organs. This statement, pictorialized in Figure 8, is the cardinal principle of vestibular mechanics. How the reactive torques and gravito-inertial forces stimulate the hair cells of the cristae and maculae, respectively, and produce changes in frequency of action potentials in the associated vestibular neurons, has already been described. The resulting frequency-coded messages are transmitted into the several central vestibular projection areas as raw orientational data, to be further processed as necessary for the various functions served by such data. These functions are: the vestibular reflexes, voluntary movement, and perception of orientation.

Vestibular Reflexes. As stated so adequately by Melvill Jones (13), "...for control of eye movement relative to space the motor outflow can operate on three fairly discrete anatomical platforms, namely: (1) the eye-in-skull platform, driven by the external eye muscles rotating the eyeball relative to the skull; (2) the skull-on-body platform driven by the neck muscles; and

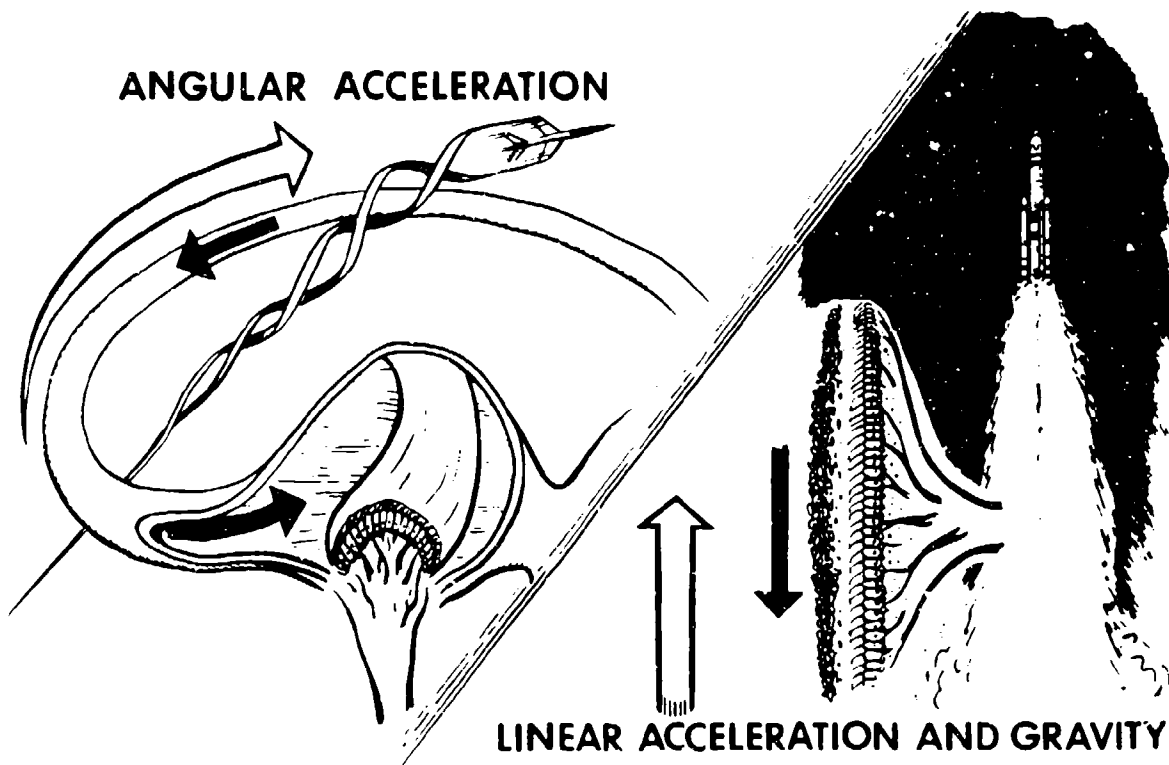


Figure 8. The cardinal principle of vestibular mechanics: angular accelerations stimulate the semicircular ducts; linear accelerations and gravity stimulate the otolith organs.

(3) the body platform, operated by the complex neuromuscular mechanisms responsible for postural control."

In humans the retinal image is stabilized mainly by vestibulo-ocular reflexes, primarily those of semicircular-duct origin. A simple demonstration can help one appreciate the contribution of vestibulo-ocular reflexes to retinal-image stabilization. Holding the extended fingers half a meter or so in front of the face, one can move them slowly from side to side and still see them clearly because of visual (optokinetic) tracking reflexes. But as the rate, or correspondingly, the frequency, of movement becomes greater, one eventually reaches a point where he is unable to see his fingers clearly--they are blurred by the movement. This point is at about 60 degrees per second or one to two cycles per second for most people. Now if one holds his fingers still, and rotates his head back and forth at the frequency at which the fingers became blurred when they were moved, the fingers remain perfectly clear. Even at considerably higher frequencies of head movement, the vestibulo-ocular reflexes initiated by the resulting stimulation of the

semicircular ducts function to keep the image of the fingers clear. Thus, at lower frequencies of movement of the external world relative to the body or vice versa, the visual system stabilizes the retinal image by means of optokinetic reflexes. But as the frequencies of such relative movement become greater, the vestibular system, by means of vestibulo-ocular reflexes, assumes progressively more of this function; and at the higher frequencies of relative motion characteristically generated only by motions of the head and body, the vestibular system is the one stabilizing the retinal image.

The mechanism by which stimulation of the semicircular ducts results in retinal image stabilization is quite simple, at least conceptually (Fig. 9). When the head is turned to the right in the horizontal (yaw) plane, the angular acceleration of the head creates a reactive torque in the ring of endolymph in (mainly) the horizontal semicircular duct. The reacting endolymph thereupon exerts pressure on the cupula, deviating the cupula in the right ear in a utriculopetal direction, depolarizing the hair cells of the associated crista ampullaris, and increasing the frequency of the action potentials in the corresponding ampullary nerve. In the left ear the endolymph deviates the cupula in a utriculofugal direction, thereby hyperpolarizing the hair cells and decreasing the frequency of the action potentials generated. As excitatory neural signals are relayed to the contralateral lateral rectus and ipsilateral medial rectus muscles, and inhibitory signals are simultaneously relayed to the antagonists, a conjugate deviation of the eyes results from the described changes in ampullary neural activity. The direction of this conjugate eye deviation is thus the same as that of the angular reaction of the endolymph, and the angular velocity of the deviation is proportional to the pressure exerted by the endolymph on the cupula. The resulting eye movement is therefore compensatory; i.e., it adjusts the angular position of the eye to compensate for changes in angular position of the head, and thereby prevents slippage of the retinal image over the retina. Because the amount of angular deviation of the eye is physically limited, very rapid movements of the eye in the direction opposite the compensatory motion are employed to return the eye to its initial position or to advance it to a position from which it can sustain a compensatory sweep for a suitable length of time. These very rapid eye movements are anticompensatory, and because of their very high angular velocity, we do not perceive motion during this phase of the vestibulo-ocular reflex.

With the usual rapid, high-frequency rotations of the head, the rotational inertia of the endolymph acts to deviate the cupula as the angular velocity of the head builds, and the angular momentum gained by the endolymph during the brief acceleration acts to drive the cupula back to its resting position when the head decelerates to a stop. The cupula-endolymph system thus functions as an integrating angular accelerometer; i.e. it converts angular acceleration data into

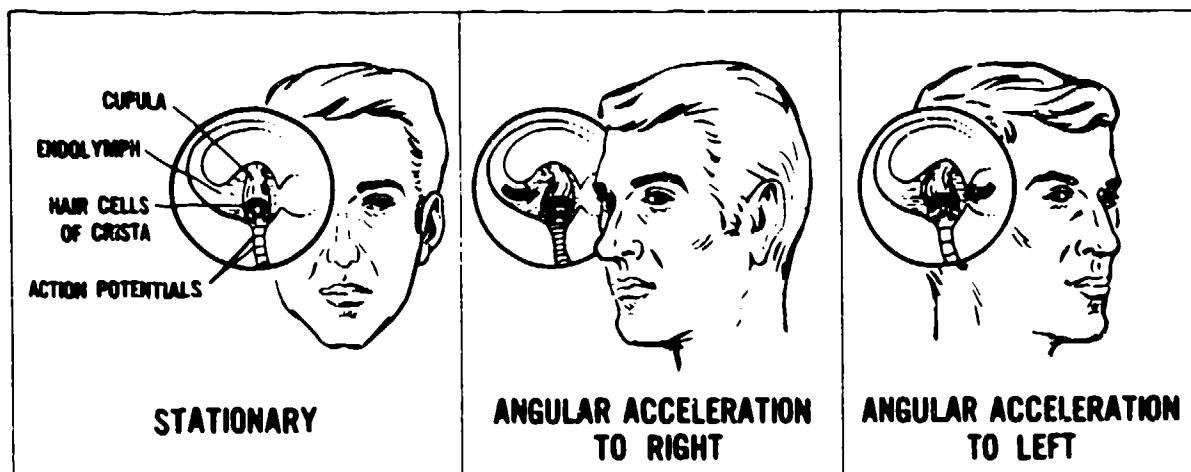


Figure 9. Mechanism of action of a horizontal semicircular duct, and resulting reflex eye movement. Angular acceleration to the right increases the frequency of action potentials originating in the right ampullary nerve and decreases those in the left. This pattern of neural signals causes extraocular muscles to rotate the eyes in the direction opposite that of head rotation, thus stabilizing the retinal image with a compensatory eye movement. Angular acceleration to the left has the opposite effect.

a neural signal proportional to the angular velocity of the head. This is true for angular accelerations occurring at frequencies normally encountered in terrestrial activities; when angular accelerations outside the dynamic response range of the cupula-endolymph system are experienced, the system no longer provides accurate angular velocity information. When angular accelerations are relatively sustained, or a cupula is kept in a deviated position by other means, such as caloric testing, the compensatory and anticomensatory phases of the vestibulo-ocular reflex are repeated, resulting in beats of ocular nystagmus (Fig. 10). The compensatory phase of the vestibulo-ocular reflex is then called the slow phase of nystagmus, and the anticomensatory phase is the fast or quick phase. The direction of the quick phase is used to label the direction of the nystagmus, as the direction of the rapid motion of the eye is the easier to determine clinically. The vertical semicircular ducts operate in an analogous manner, with the vestibulo-ocular reflexes elicited by their stimulation being appropriate to the plane of the angular acceleration resulting in that stimulation. Thus, a vestibulo-ocular reflex with downward compensatory and upward anticomensatory phases results from stimulation of the vertical semicircular ducts by pitch-up ($-\alpha_y$) angular acceleration, and with sufficient stimulation in this plane, up-beating

vertical nystagmus results. Angular accelerations in the roll plane quite logically result in vestibulo-ocular reflexes with clockwise and counterclockwise compensatory and anticompensatory phases, and in rotary nystagmus. Other planes of stimulation are associated with other directions of eye movement, such as oblique or horizonto-rotary.

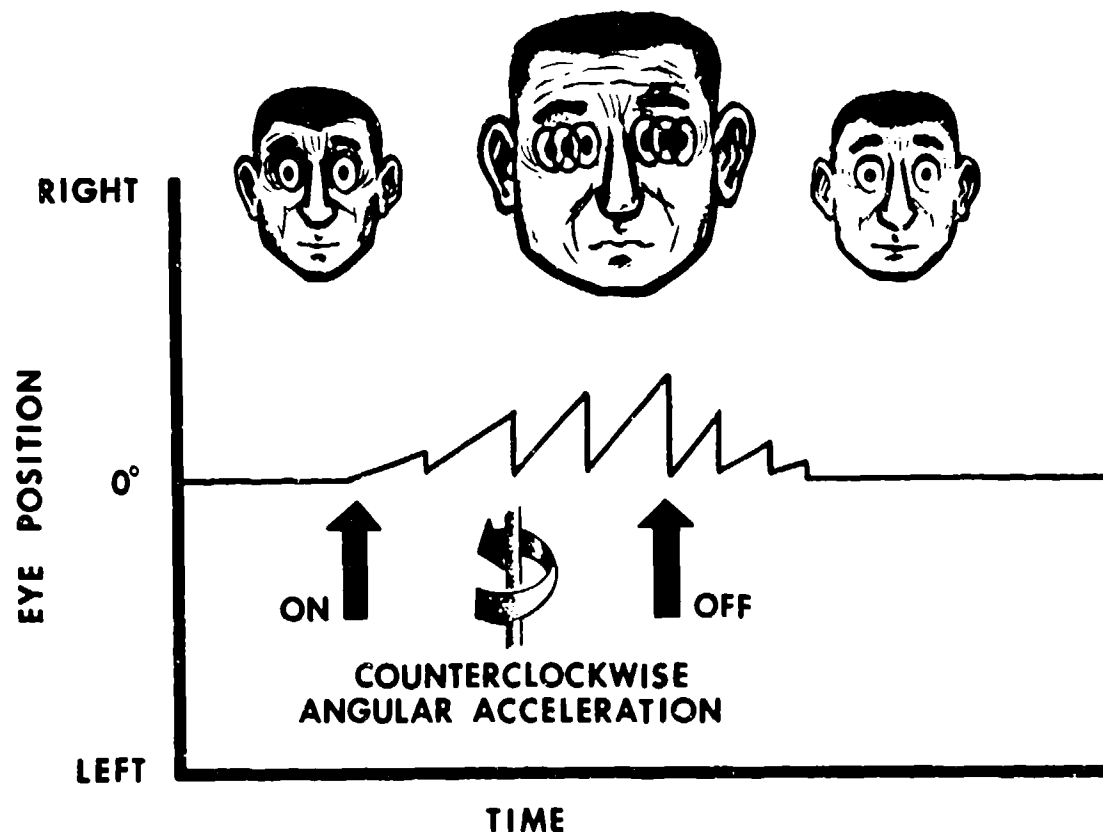


Figure 10. Ocular nystagmus--repeating compensatory and anti-compensatory eye movements--resulting from vestibular stimulation. In this case the stimulation is a yawing angular acceleration to the left, and the anti-compensatory, or quick-phase, nystagmic response is also to the left.

As should be expected, there are also vestibulo-ocular reflexes of otolith-organ origin. Initiating these reflexes are the shearing actions that bend the cilia of macular hair cells as inertial forces or gravity cause the otolithic membranes to slide to various positions over their maculae (Fig. 11). Each position that can be assumed by an otolithic membrane relative to its macula evokes a particular spatial pattern of frequencies of action potentials in the corresponding utricular or saccular nerve; and that pattern is associated with a particular set of compatible stimulus conditions, such as backward tilt of the

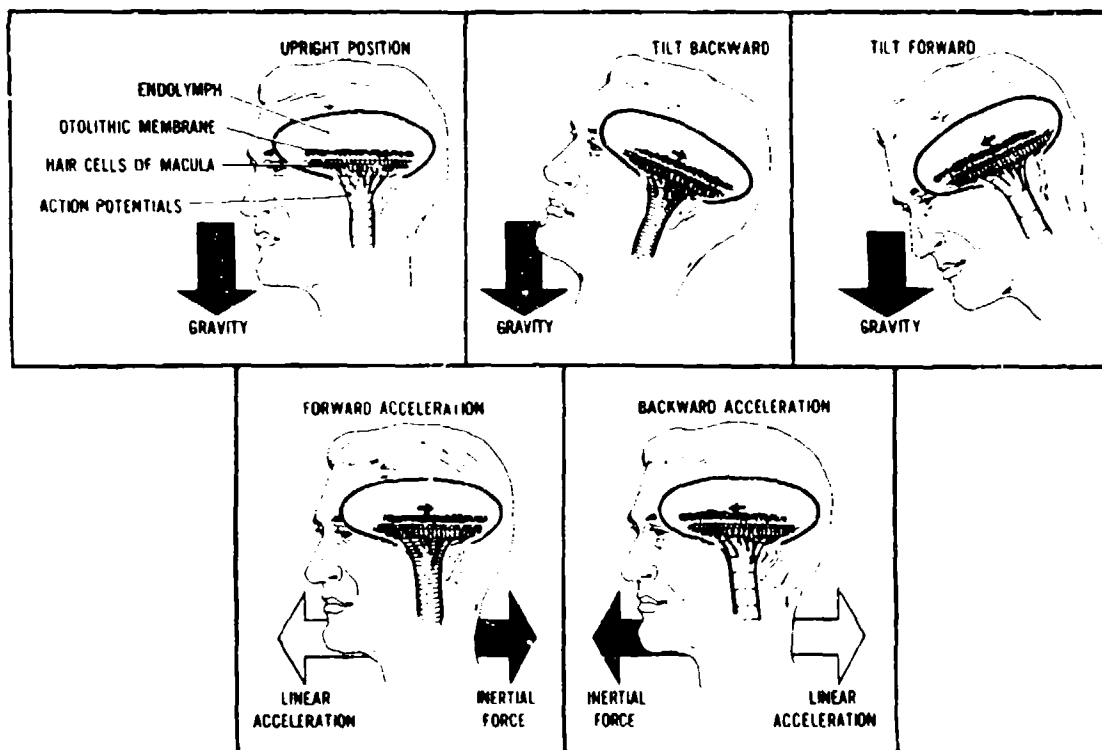


Figure 11. Mechanism of action of an otolith organ. A change in direction of the force of gravity (above) or a linear acceleration (below) causes the otolithic membrane to shift its position with respect to its macula, thereby generating a new pattern of action potentials in the utricular or saccular nerve. Shifting of the otolithic membranes can elicit compensatory vestibulo-ocular reflexes as well as perceptual effects.

head or forward linear acceleration. These patterns of action potentials from the various otolith organs are correlated and integrated in the vestibular nuclei and cerebellum with orientational information from the semicircular ducts and other sensory modalities; appropriate orientational percepts and motor activities eventually result. Lateral (a_y) linear accelerations can elicit horizontal reflexive eye movements, including nystagmus, presumably as a result of utricular stimulation. Similarly, vertical (a_z) linear accelerations can elicit vertical eye movements, most likely as a result of stimulation of the saccule; the term elevator reflex is sometimes used to describe this response, as it is readily provoked by the vertical linear accelerations associated with riding in an elevator. The utility of these horizontal and vertical vestibulo-ocular reflexes of otolith-organ origin is readily apparent: like the reflexes of semicircular-duct origin, they help stabilize the retinal image. Less obvious is the usefulness of the ocular

countertorsion reflex (Fig. 12), which repositions the eyes about their visual (anteroposterior) axes in response to the otolith-organ stimulation resulting from tilting the head laterally in the opposite direction. Presumably this reflex contributes to retinal image stabilization by providing a response to changing directions of the force of gravity.



Figure 12. Ocular countertorsion, a vestibulo-ocular reflex of otolith-organ origin. When the head is tilted to the left, the eyes rotate to the right to assume a new angular position about the visual axes, as shown.

Our understanding of the vestibulocollic reflexes has not developed to the same degree as that of the vestibulo-ocular reflexes, although some clinical use has been made of measurements of rotation of the head on the neck in response to vestibular stimulation. Perhaps this situation reflects the fact that, in humans, vestibulocollic reflexes are not as effective as vestibulo-ocular reflexes in stabilizing the retinal image. Such is not the case in other species, however; birds exhibit extremely effective reflex control of head position under conditions of bodily motion--even nystagmic head movements are quite easy to elicit. The high level of development of the

vestibulocollic reflexes in birds is certainly either a cause or a consequence of the relative immobility of birds' eyes in their heads. Nonetheless, the ability of a human (or any other vertebrate with a mobile head) to keep his head upright with respect to the direction of applied gravito-inertial force is maintained through tonic vestibular influences on the muscles of the neck.

Vestibulospinal reflexes operate to assure stability of the body. Transient linear and angular accelerations, such as those experienced in tripping and falling, provoke rapid activation of various groups of extensor and flexor muscles, so as to return the body to the stable position or at least to minimize the ultimate effect of the instability. We have all experienced the reflex arm movements that serve to break a fall, and have observed the more highly developed righting reflexes that cats exhibit when dropped from an upside-down position; these are examples of vestibulospinal reflexes. Less spectacular, but nevertheless extremely important, are the sustained vestibular influences on posture, exerted through tonic activation of so-called "antigravity" muscles such as hip and knee extensors. These vestibular reflexes, of course, help keep the body upright with respect to the direction of the force of gravity.

Voluntary Movement. We have seen how the various reflexes of vestibular origin serve to stabilize the body in general and the retinal image in particular. But the vestibular system is also important in that it provides data for the proper execution of voluntary movement. To realize just how important such vestibular data are in this context, we must first recognize the fact that skilled voluntary movements are ballistic--i.e., once initiated, they are executed according to a predetermined pattern and sequence, without the benefit of simultaneous sensory feedback to the higher neural levels from which they originate. The simple act of writing one's signature, for example, involves such rapid changes in speed and direction of movement that conscious sensory feedback and adjustment of motor activity are virtually precluded, at least until the act is nearly completed. Learning an element of a skill thus involves developing a computer-program-like schedule of neural activations that can be called up, so to speak, to effect a particular desired end product of motor activity. Of course, the raw program for a particular voluntary action is not sufficient to permit the execution of that action: information regarding such parameters as intended magnitude and direction of movement must be furnished from the conscious sphere, and data indicating the position and motion of the body platform relative to the surface of the earth--i.e., spatial orientation information--must be furnished from the preconscious. The necessity for the additional information is seen when we consider the signature-writing example cited above, and realize that we can write large or small, quickly or slowly, and on a horizontal or vertical surface. Obviously, different patterns of neuromuscular activation, even grossly different muscle groups, are needed to

accomplish a basic act under varying spatial and temporal conditions; but the necessary adjustments are made automatically, without conscious intervention. Vestibular and other sensory data providing spatial orientation information for use in either skilled voluntary or reflexive motor activity are processed into a preconscious orientational percept that provides the informational basis upon which such automatic adjustments are made. Thus, without having consciously to discern the direction of the force of gravity, analyze its potential effects on planned motor activity, select appropriate muscle groups and modes of activation to compensate for gravity, and then activate and deactivate each muscle in proper sequence and with proper timing to accomplish the desired motor activity, we simply decide what we want the outcome of our action to be and initiate the command to do it. Our body takes care of the details, using stored programs for elements of skilled motor activity, and the current preconscious orientational percept. This whole process is the major function and responsibility of the vestibulo-cerebellar axis.

Conscious Percepts. Usually as a result of the same information processing that provides the preconscious orientational percept, one is also provided a conscious orientational percept. This percept can be false, i.e., illusory, in which case the subject is said to experience an orientational illusion. (The term pilot vertigo refers to an illusory conscious orientational percept experienced by a pilot. Although clinical use of the word vertigo usually, but by no means always, denotes a pronounced sensation of turning, in aeromedical usage no such sensation is implied--only a false conscious orientational percept.) One can be aware, moreover, that what his body is telling him about his spatial orientation is not what he has concluded from other information, such as flight instrument data. Conscious orientational percepts thus can be either natural or derived, depending on the source of the orientation information and the perceptual process involved; and one can experience both natural and derived conscious orientational percepts at the same time. Because of this, pilots who have become disoriented in flight commonly exhibit vacillating control inputs, as they alternate indecisively between responding first to one percept and then to the other.

Thresholds of Vestibular Perception. Often an orientational illusion occurs because the physical event resulting in or from a change in bodily orientation is below the threshold of perception. For that reason, the student of disorientation should be aware of the approximate perceptual thresholds associated with the various modes of vestibular stimulation.

The lowest reported threshold for perception of rotation is $0.035 \text{ degrees/s}^2$, but this degree of sensitivity is obtained only with virtually continuous angular acceleration and long response latencies (20 to 40 seconds) (14). Other observations put the perceptual threshold between roughly 0.1 and 2.0 degrees/s^2 ; reasonable values are 0.14 , 0.5 , and

0.5 degrees/s² for yaw, roll, and pitch motions, respectively (15). It is common practice, however, to describe the thresholds of the semicircular ducts in terms of the angular acceleration-time product, or angular velocity, which results in just perceptible rotation. This product remains fairly constant for stimulus times of about five seconds or less, and is known as Mulder's constant--even though the observed values of this constant range between 0.2 and 8.0 degrees/s, depending on the subjects and methods used to determine it. Using the reasonable value of 2 degrees/s for Mulder's constant, we find that an angular acceleration of 5 degrees/s² applied for half a second would be perceived because the acceleration-time product is above the 2-degrees/s angular velocity threshold. But a 10-degrees/s² acceleration applied for a tenth of a second would not be perceived, because it would be below the angular velocity threshold; nor would a 0.2-degrees/s² acceleration applied for 5 s.

The perceptual threshold related to otolith-organ function necessarily involves both an angle and a magnitude, as the otolith organs respond to linear accelerations and gravito-inertial forces, both of which have direction and intensity. A 1.5-degree change in direction of applied G force is perceptible under ideal (experimental) conditions. The minimum perceptible intensity of linear acceleration has been reported by various authors to be between 0.001 and 0.03 g, depending on direction of acceleration and experimental method used. Values of 0.01 g for a_z and 0.006 g for a_x accelerations are appropriate representative thresholds, and a similar value for a_y acceleration is probably reasonable (15). Again, these absolute thresholds apply when the acceleration is either sustained or applied at relatively low frequencies. The threshold for linear accelerations applied for less than about 5 s is a more or less constant acceleration-time product, or linear velocity, of about 0.3-0.4 m/s.

Unfortunately for those who would like to calculate exactly what orientational percept results from a particular set of linear and angular accelerations, such as might have occurred prior to an aircraft mishap, the actual vestibular perceptual thresholds are, as expressed by one philosopher, "constant except when they vary." Probably the most common reason for an orientational perceptual threshold to be raised is inattention to orientational cues because of attention to something else. Other reasons might be low state of mental arousal, fatigue, drug effects, or innate individual variation. Whatever the reason, it appears that a given individual can monitor his orientation with considerable sensitivity under some circumstances and relative insensitivity under others, which inconsistency can itself lead to perceptual errors that result in orientational illusions.

Of paramount importance in the generation of orientational illusions, however, is not the fact that absolute vestibular thresholds exist, or that vestibular thresholds are time-varying. Rather, it is the fact that the components of the vestibular system, like those of any complex mechanical or electrical system, have characteristic frequency responses; and stimulation by patterns of acceleration outside the optimum, or "design," frequency-response ranges of the semicircular ducts and otolith organs causes the vestibular system to make errors. In flight, much of the stimulation resulting from the acceleratory environment is indeed outside the design frequency-response ranges of the vestibular end-organs; consequently, orientational illusions occur in flight. Elucidation of this important point is provided in the section on spatial disorientation.

Vestibular Suppression and Enhancement. Like all sensory systems, the vestibular system exhibits a decreased response to stimuli that are persistent (adaptation) or repetitious (habituation). Even more important to the aviator is the fact that, with time and practice, one can develop the ability to suppress natural vestibular responses, both perceptual and motor. This ability is termed vestibular suppression. Closely related to the concept of vestibular suppression is that of visual dominance, the ability to obtain and use spatial orientation cues from the visual environment despite the presence of potentially very strong vestibular cues. Vestibular suppression seems to be exerted, in fact, through visual dominance, as it disappears in the absence of vision. The opposite effect, that of an increase in perceptual and motor responsiveness to vestibular stimulation, is termed vestibular enhancement. Such enhancement can occur when the stimulation is novel, as in an amusement park ride, or threatening, as in an aircraft spinning out of control, or whenever spatial orientation is perceived to be especially important. It is tempting to attribute to the efferent vestibular neurons the function of controlling the gain of the vestibular system so as to effect suppression and enhancement, and some evidence exists to support that notion (16). The actual mechanisms involved appear to be much more complex than would be necessary to merely provide gross changes in gain of the vestibular end-organs. Very precise control of vestibular responses to anticipated stimulation, based on sensory efferent copies of voluntary commands for movement, is probably exercised by the cerebellum via a feed-forward loop involving the vestibular efferent system. Thus, when discrepancies between anticipated and actual stimulation generate a neural error signal, a response is evoked, and vestibular reflexes and heightened perception occur (17). Vestibular suppression, then, involves the development of accurate estimates of vestibular responses to orientational stimuli repeatedly experienced, and the active countering of anticipated responses by spatially and temporally patterned sensory efferent activity. Vestibular enhancement, on the other hand, results from the lack of available estimates of vestibular responses because of the novelty of the stimulation, or perhaps from a revision in neural processing strategy obligated by the

failure of normal negative feed-forward mechanisms to provide adequate orientation information. Such marvelous complexity of vestibular function assures adaptability to a wide variety of motional environments, and thereby promotes survival in them.

OTHER SENSES OF MOTION AND POSITION

Although the visual and vestibular systems play dominant roles in spatial orientation, the contributions of other sensory systems to orientation cannot be overlooked. Especially important are the nonvestibular proprioceptors--the muscle, tendon, and joint receptors--and the cutaneous exteroceptors, as the orientational percepts derived from their functioning in flight generally support those derived from vestibular information processing, whether accurate or inaccurate. The utility of these other sensory modalities is appreciated when we realize that, in the absence of vision, our vestibular, muscle, tendon, joint, and skin receptors allow us to maintain spatial orientation and postural equilibrium, at least on the earth's surface. Similarly, in the absence of vestibular function, vision and the remaining proprioceptors and cutaneous mechanoreceptors are sufficient for orientation and balance. But when two components of this triad of orientational senses are absent or substantially compromised, we are unable to maintain sufficient spatial orientation to permit postural stability and effective locomotion. The following limited discussion of the nonvisual, nonvestibular, orientational sensory modalities is not meant to imply that they are either unstudied or uninteresting. On the contrary, a large, fascinating body of knowledge has accumulated in this area, and the reader is referred elsewhere for comprehensive reviews of this subject matter (18,19).

Nonvestibular Proprioceptors

Sherrington's "proprioceptive" or "self-sensing" sensory category includes the vestibular (or labyrinthine), muscle, tendon, and joint senses. We commonly speak of proprioception as though it means only the nonvestibular components, however.

Muscle and Tendon Senses. Skeletal muscle contains within it complex sensory end-organs, muscle spindles (Fig. 13a). These end-organs are comprised mainly of small intrafusal muscle fibers that lie in parallel with the larger, ordinary, extrafusal muscle fibers, and are enclosed over part of their length by a fluid-filled bag. The sensory innervation of these structures consists mainly of large, rapidly conducting afferent neurons that originate as primary (annulospiral) or secondary (flower-spray) endings on the intrafusal fibers and terminate in the spinal cord on anterior horn cells and interneurons. Stretching of the associated extrafusal muscle results in an increase in frequency of action potentials in the afferent nerve from the intrafusal fibers; contraction of the muscle results in a decrease or absence of action potentials. The more interesting aspect of muscle spindle function, however, is that the intrafusal muscle fibers are innervated by motor neurons (gamma efferents and

others) and can be stimulated to contract, thereby altering the afferent information arising from the spindle. Thus, the sensory input from the muscle spindles can be biased by descending influences from higher neural centers, such as the vestibulo-cerebellar axis.

While the muscle spindles are structurally and functionally in parallel with associated muscle groups and respond to changes in their length, the Golgi tendon organs (Fig. 13b) are functionally in series with the muscles and respond to changes in tension. A tendon organ consists of a fusiform bundle of small tendon fascicles with intertwining neural elements, and is located at the musculotendinous junction or wholly within tendon. Unlike that of the muscle spindle, its innervation is entirely afferent.

The major function of muscle spindles and tendon organs is to provide the sensory basis for myotatic (or muscle stretch) reflexes. These elementary spinal reflexes operate to stabilize a joint by providing, in response to an increase in length of a muscle and concomitant stimulation of its included spindles, monosynaptic excitation and contraction of the stretched agonist (e.g., extensor) muscle, and disynaptic inhibition and relaxation of its antagonist (e.g., flexor) through the action of an inhibitory interneuron. In addition, tension developed on associated tendon organs results in disynaptic inhibition of the agonist muscle, thus regulating the amount of contraction generated. The myotatic reflex mechanism is, in fact, at the very foundation of posture and locomotion. Modification of this and other basic spinal reflexes by organized facilitatory or inhibitory intervention originating at higher neural levels, either through direct action on skeletomotor (alpha) neurons or through stimulation of fusimotor (primarily gamma) neurons to muscle spindles, results in sustained postural equilibrium and other purposive motor behavior. Some have speculated, moreover, that in certain types of spatial disorientation in flight, this organized modification of spinal reflexes is interrupted, as cerebral cortical control of motor activity is replaced by lower brainstem and spinal control. Perhaps the "frozen-on-the-controls" type of disorientation-induced deterioration of flying ability is a reflection of primitive reflexes made manifest by disorganization of higher neural functions.

Despite the obvious importance of the muscle spindles and tendon organs in control of motor activity, there is little evidence to indicate that their responding to orientational stimuli (such as occur when one stands vertically in a 1-G environment) results in any corresponding conscious proprioceptive percept (20). Nevertheless, it is known that the dorsal columns and other ascending spinal tracts carry muscle afferent information to medullary and thalamic relay nuclei, and thence to the cerebral sensory cortex. Furthermore, extensive projections into the cerebellum from the afferent terminations of the muscle spindles and tendon organs--via dorsal and ventral

spinocerebellar tracts--ensure that proprioceptive information from these receptors is integrated with other orientational information and is relayed to the vestibular nuclei, cerebral cortex, and elsewhere as needed.

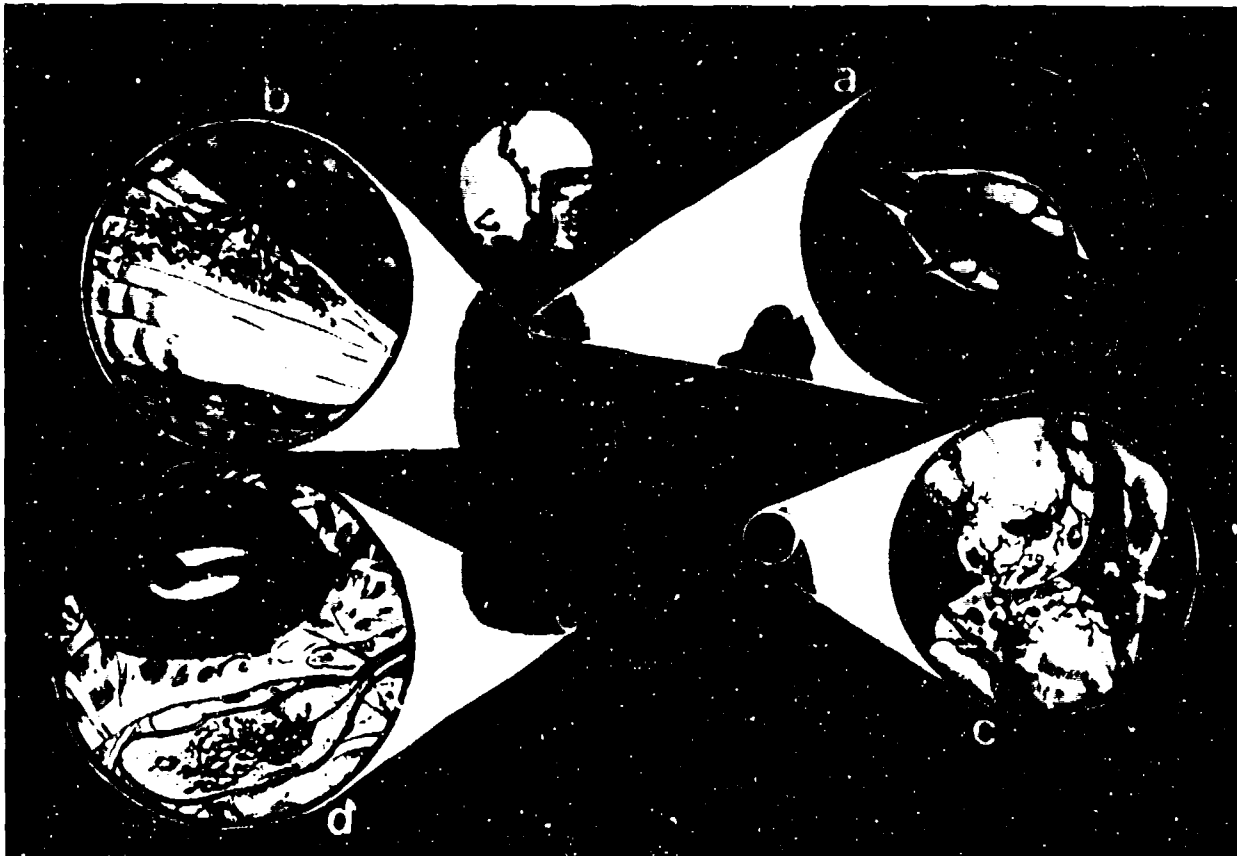


Figure 13. Some of the nonvestibular proprioceptive and cutaneous exteroceptive receptors subserving spatial orientation. a. Muscle spindle, with central afferent (sensory) and more peripheral efferent (fusimotor) innervation shown. b. Golgi tendon organ. c. Lamellated, spray-type, and free-nerve-ending joint receptors. d. Two of the many types of mechanoreceptors found in skin: lamellated Pacinian corpuscles and spray-type Ruffini corpuscles.

Joint Sensation. In contrast to the situation with the so-called "muscle sense of position" discussed above, it is well established that sensory information from the joints does reach consciousness. In fact, the threshold for perception of joint motion and position can be quite low: as low as 0.5 degrees for the knee joint when moved at greater than 1.0 degrees/s. The receptors in the joints are of three types, as shown in Fig. 13c:

(1) lamellated or encapsulated Pacinian corpuscle-like end-organs; (2) spray-type structures, known as Ruffini-like endings when found in joint capsules and Golgi tendon organs when found in ligaments; and (3) free nerve endings. The Pacinian corpuscle-like terminals are rapidly adapting and are sensitive to quick movement of the joint, whereas both of the spray-type endings are slowly adapting and serve to signal slow joint movement and joint position. There is evidence that polysynaptic spinal reflexes can be elicited by stimulation of joint receptors, but their nature and extent are not well understood. Proprioceptive information from the joint receptors projects via the dorsal funiculi eventually to the cerebral sensory cortex, and via the spinocerebellar tracts to the anterior lobe of the cerebellum.

One must not infer from this discussion that only muscles, tendons, and joints have proprioceptive sensory receptors. Both lamellated and spray-type receptors, as well as free nerve endings, are found in fascia, aponeuroses, and other connective tissues of the musculoskeletal system; and presumably they provide proprioceptive information to the central nervous system.

Cutaneous Exteroceptors

The exteroceptors of the skin include the mechanoreceptors, which respond to touch and pressure; thermoreceptors, which respond to heat and cold; and nociceptors, which respond to noxious mechanical and/or thermal events and give rise to sensations of pain. Of the cutaneous exteroceptors, only the mechanoreceptors contribute significantly to spatial orientation.

Mechanoreceptors. Quite a variety of receptors are involved in cutaneous mechanoreception: spray-type Ruffini corpuscles; lamellated Pacinian and Meissner corpuscles; branched and straight lanceolate terminals, Merkel cells, and free nerve endings (Fig. 13D). The response patterns of the mechanoreceptors are also numerous: eleven different types of response, varying from high-frequency transient detection, through several modes of velocity detection, to more or less static displacement detection, are recognized. Pacinian corpuscles and certain receptors associated with hair follicles are very rapidly adapting and have the highest mechanical frequency responses, responding to sinusoidal skin displacements in the range of 50 to 400 Hz. They are thus well suited to monitor vibration and very transient touch stimuli. Ruffini corpuscles are slowly adapting and therefore respond primarily to low-frequency, i.e., sustained, touch and pressure stimuli. Merkel cells appear to have a moderately slowly adapting response, making them suitable for monitoring static skin displacement and velocity. Meissner corpuscles seem to detect primarily velocity of skin deformation. Other receptors provide other types of response, so as to complete the spectrum of mechanical stimuli that we sense through the skin. The mechanical threshold for the touch receptors is quite low--less than 0.03 dynes/cm^2 on the thumb. (In comparison with the

labyrinthine receptors subserving audition, however, this threshold is not so impressive; a 0-dB sound pressure level represents 0.0002 dynes/cm²--more than a hundred times lower.) Afferent information from the described mechanoreceptors is conveyed to the cerebral cortex mainly by way of the dorsal funiculi and medullary relay nuclei into the medial lemnisci and thalamocortical projections. The dorsal spinocerebellar and other tracts to the cerebellum provide the pathways by which cutaneous exteroceptive information reaches the cerebellum and is integrated with proprioceptive information from muscles, tendons, joints, and vestibular end-organs.

Auditory Orientation

On the surface of the earth, the ability to determine the direction of a sound source can play an important role in spatial orientation. The major auditory cues providing this ability are differences between the ears in arrival times of congruent acoustic stimuli, and interaural differences in magnitude and phase of arriving stimuli. A revolving sound source can create a sense of self-rotation and even elicit reflex compensatory and anticomensatory eye movements called audiokinetic nystagmus. In aircraft, binaural sound localization is of little use in spatial orientation because of high ambient noise levels and absence of audible external sound sources. Pilots do extract some orientation information, however, from the auditory cues provided by the rush of air past the airframe: the sound frequencies and intensities characteristic of various airspeeds and angles of attack are recognized by the experienced pilot, and he uses them in conjunction with other orientation information to create a percept of velocity and pitch attitude of his aircraft. As aircraft have become more capable, however, and the pilot has become more insulated from such acoustic stimuli, the importance of auditory orientation cues in flying has diminished.

SPATIAL DISORIENTATION

The evolution of man saw him develop over millions of years as an aquatic, terrestrial, and even arboreal creature, but never an aerial one. In this development he subjected himself to, and was subjected to, many different varieties of transient motions, but not to the relatively sustained linear and angular accelerations commonly experienced in aviation. As a result, he acquired sensory systems well suited for maneuvering under his own power on the surface of the earth but poorly suited for flying. Even the birds, whose primary mode of locomotion is flying, are unable to maintain spatial orientation and fly safely when deprived of vision by fog or cloud. Only bats seem to have developed the ability to fly without vision, and then only by replacing vision with auditory echolocation. Considering man's phylogenetic heritage, we should not be surprised that his sudden entry into the aerial environment results in a mismatch between the orientational demands of the new environment and his innate ability to orient. The manifestation of this mismatch is spatial disorientation.

Illusions in Flight

An illusion is a false percept. An orientational illusion is a false percept of one's position, attitude, or motion, relative to the plane of the earth's surface. Thus, misperceptions of displacement, velocity, or acceleration--either linear or angular--result in orientational illusions. A great variety of orientational illusions occur during flight: some named, some unnamed; some understood, some not understood. Those that are sufficiently impressive to cause pilots to report them, whether because of their repeatability or because of their emotional impact, have been described in the aeromedical literature, and will be discussed here. We categorize the illusions in flight into those resulting primarily from visual misperceptions and those involving primarily vestibular errors.

Visual Illusions. There are two different modes of visual processing, the focal (foveal) mode and the ambient (peripheral) mode. Generally speaking, focal vision is concerned with object recognition and ambient vision is concerned with spatial orientation. But some visual orientation tasks in flying--e.g., approach to landing--require a great deal of focal vision, and such tasks can be made extremely difficult by illusions resulting from misinterpretation of focal visual cues. The runway illusions and approach illusions are illustrative of this (21).

Figure 14a shows the pilot's view of the runway during an approach to landing, and demonstrates the linear perspective and foreshortening of the runway that the pilot associates with a

3-degree approach slope. If the runway slopes upward 1 degree (a rise of only 35 m in a 2-km runway), the foreshortening of the runway for a pilot on a 3-degree approach slope is substantially less (the height of the retinal image of the runway is greater) than it would be if the runway were level. This can give the illusion of being too high on the approach. The pilot's natural response to such an illusion is to reshape his image of the runway by seeking a shallower approach slope (Fig. 14b). This response, of course, could be hazardous. The opposite situation results when the runway slopes downward. To perceive the accustomed runway shape under this condition, the pilot must fly a steeper approach slope than usual (Fig. 14c).

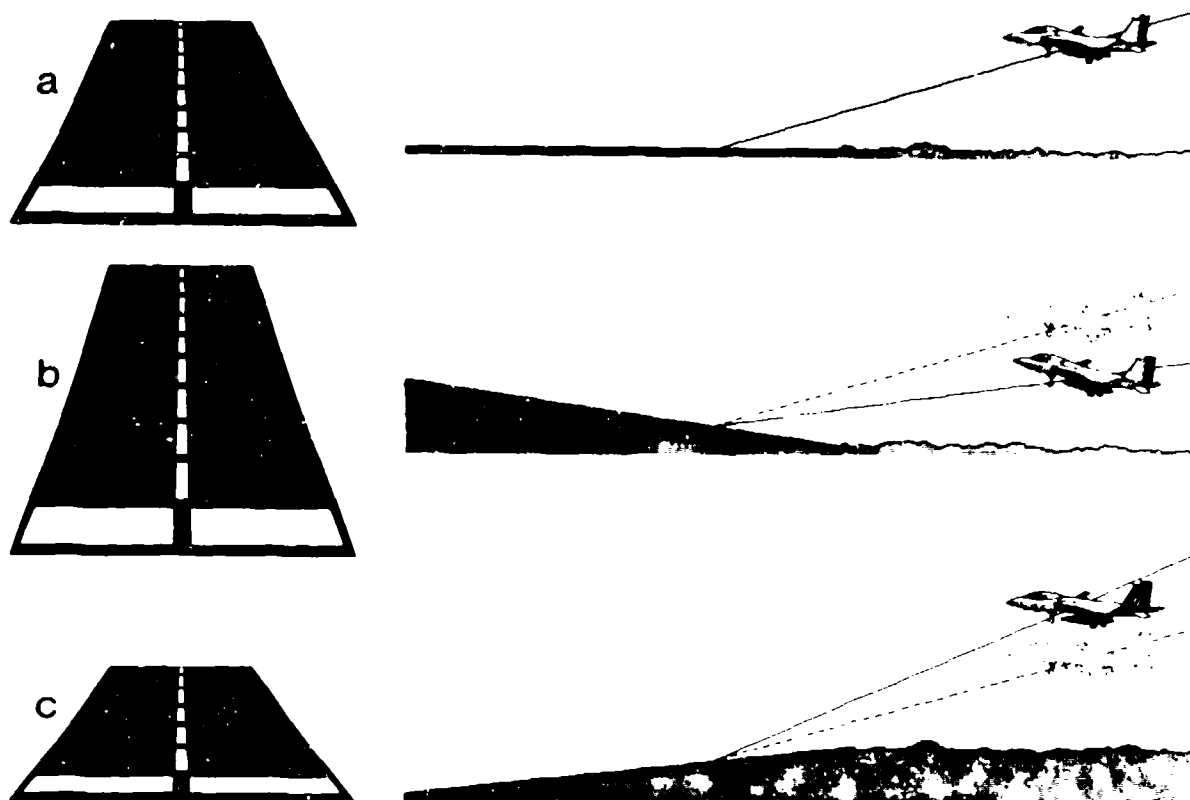


Figure 14. Effect of runway slope on pilot's image of runway during final approach (left) and potential effect on approach slope angle flown (right). a. Flat runway--normal approach. b. Upsloping runway creates illusion of being high on approach--pilot flies approach too low. c. Downsloping runway has opposite effect.

A runway that is narrower than that to which a pilot is accustomed can also create a hazardous illusion on the approach to landing. The pilot tends to perceive the narrow runway to be longer and farther away (i.e., that he is higher) than is

actually the case, and he may flare too late and touch down sooner than he expects (Fig. 15b). Likewise, a runway that is wider than what a pilot is used to can lead him to believe he is closer to the runway (i.e., lower) than he really is, and he may flare too soon and drop in from too high above the runway (Fig. 15c). Both of these runway-width illusions are especially troublesome at night, when peripheral visual orientation cues are largely absent. The very common tendency for pilots to flare too high at night results at least partly from the fact that the runway lights, being displaced laterally from the actual edge of the runway, make the runway seem wider, and therefore closer, than it actually is.

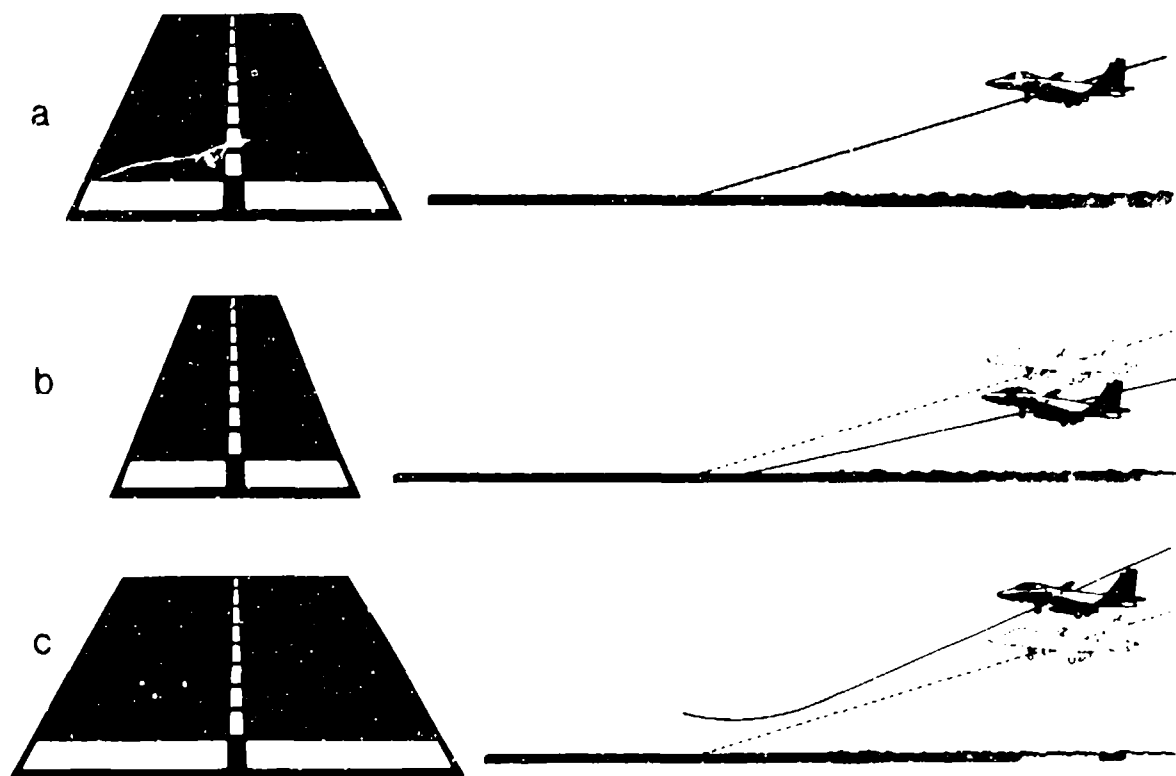
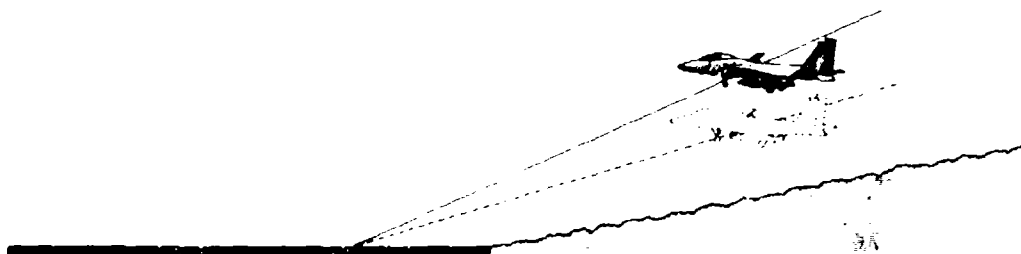


Figure 15. Effect of runway width on pilot's image of runway (left) and potential effect on approach flown (right). a. Accustomed width--normal approach. b. Narrow runway makes pilot feel he is higher than he actually is, so he flies approach too low and flares too late. c. Wide runway appears closer than it actually is--pilot tends to approach too high and flare too soon.

The slope and composition of the terrain under the approach path can also influence the pilot's judgment of his height above the touchdown point. If the terrain descends to the approach

end of the runway, the pilot tends to fly a steeper approach than he would if the approach terrain were level (Fig. 16a). If the approach terrain slopes up to the runway, on the other hand, the pilot tends to fly a less steep approach than he would otherwise (Fig. 16b). Although estimation of height above the approach terrain depends on both focal and ambient vision, the contribution of focal vision is particularly clear: consider the pilot who looks at a building below him, and seeing it to be closer than such buildings usually are, he seeks a higher approach slope. By the same token, focal vision and size constancy are responsible for poor height and distance judgments pilots sometimes make when flying over terrain having an unfamiliar composition (Fig. 17). A reported example of this is the tendency to misjudge approach height when landing in the Aleutians, where the evergreen trees are much smaller than those to which most pilots are accustomed. Such height-estimation difficulties are by no means restricted to the approach and landing phases of flight. One fatal mishap occurred during air combat training over the Southwest Desert, when the pilot of a high-performance fighter apparently misjudged his height over the desert floor because of the small, sparse vegetation, and was unable to arrest in time his deliberate descent to a ground-hugging altitude.

a



b

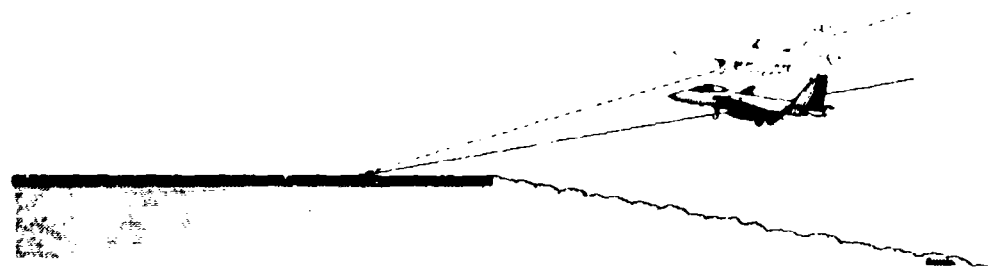


Figure 16. Potential effect of slope of terrain under the approach on approach slope flown. a. Terrain slopes down to runway; pilot perceives himself to be too shallow on approach and steepens it. b. Upsloping terrain makes pilot think he is too high, so he corrects by making approach too shallow.

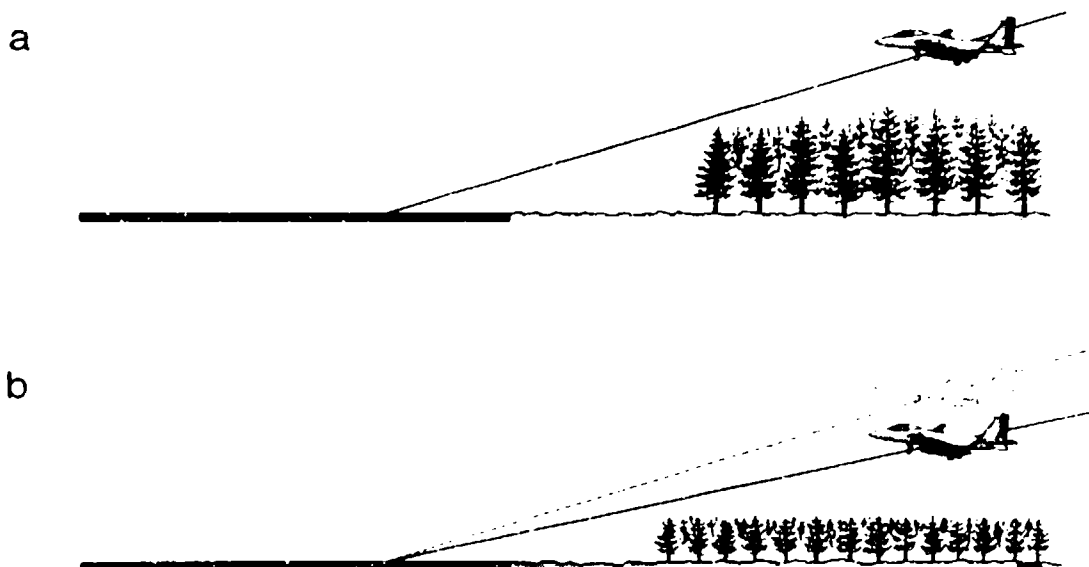


Figure 17. Potential effect of unfamiliar composition of approach terrain on approach slope flown. a. Normal approach over trees of familiar size. b. Unusually small trees under approach path make pilot think he is too high, so he makes his approach lower than usual.

A well-known pair of approach-to-landing situations that create illusions because of the absence of adequate focal visual orientation cues are the smooth-water (or glassy-water) and snow-covered approaches. A seaplane pilot's perception of height is degraded substantially when the water below is still: for that reason he routinely just sets up a safe descent rate and waits for the seaplane to touch down, rather than attempting to flare to a landing, when the water is smooth. A blanket of fresh snow on the ground also deprives the pilot of visual cues with which to estimate his height, thus making his approach more difficult--extremely difficult if the runway is also covered with snow. Again, approaches are not the only regime in which smooth water and fresh snow cause problems. A number of aircraft have crashed as a result of pilots' maneuvering over smooth water or snow-covered ground and misjudging their height above the water or ground.

Aerial perspective can also play a role in deceiving the pilot. In daytime, fog or haze can make a runway appear farther away as a result of the loss of visual discrimination. At night, runway and approach lights in fog or rain appear less bright than they do in clear weather, and can create the illusion that they are farther away. It has even been reported that a pilot can have an illusion of banking to the right, for example, if the runway lights are brighter on the right side of the runway than

they are on the left. Another hazardous illusion of this type can occur during approach to landing in a shallow fog or haze, especially during a night approach. The vertical visibility under such conditions is much better than the horizontal visibility, so that descent into the fog causes the more distant approach or runway lights to diminish in intensity, at the same time that peripheral visual cues are suddenly occluded by the fog. The result is an illusion that the aircraft has pitched up, with the concomitant danger of a nose-down corrective action by the pilot.

Another condition in which a pilot is apt to make a serious misjudgment is in closing on another aircraft at high speed. When he has numerous peripheral visual cues by which to establish his own position and velocity relative to the earth and the target's position and velocity relative to the earth, his tracking and closing problem is not much different from what it would be on the ground if he were giving chase to a moving quarry. But when relative position and closure rate cues must come from foveal vision alone, as is generally the case at altitude, at night, or under other conditions of reduced visibility, the tracking and closing problem is much more difficult. An overshoot--or worse, a midair collision--can easily result from the perceptual difficulties inherent under such circumstances, especially when the pilot lacks experience in the environment devoid of peripheral visual cues.

Two runway approach conditions that create considerable difficulty for the pilot, and which, like the closure-rate problems discussed above, result from tasking focal vision to accomplish by itself what is normally accomplished with both focal and ambient vision, are the black-hole and whiteout approaches. A black-hole approach is one that is made on a dark night over water or unlighted terrain to a runway beyond which the horizon is indiscernible, the worst case being when only the runway lights are visible (Fig. 18). Without peripheral visual cues to help him orient himself relative to the earth, the pilot tends to feel he is stable and situated appropriately, but that the runway itself moves about or remains malpositioned (is downsloping, for example). Such illusions make the black-hole approach difficult and dangerous, and often result in a landing far short of the runway. A particularly hazardous type of black-hole approach is one made under conditions wherein the earth is totally dark except for the runway and the lights of a city on rising terrain beyond the runway. It has been observed that under these conditions the pilot tries to maintain a constant vertical visual angle for the distant city lights, thus causing his aircraft to arc far below the intended approach slope as he gets closer to the runway (Fig. 19) (22). An alternative explanation is that the pilot falsely perceives through ambient vision that the rising terrain is flat, and he lowers his approach slope accordingly.

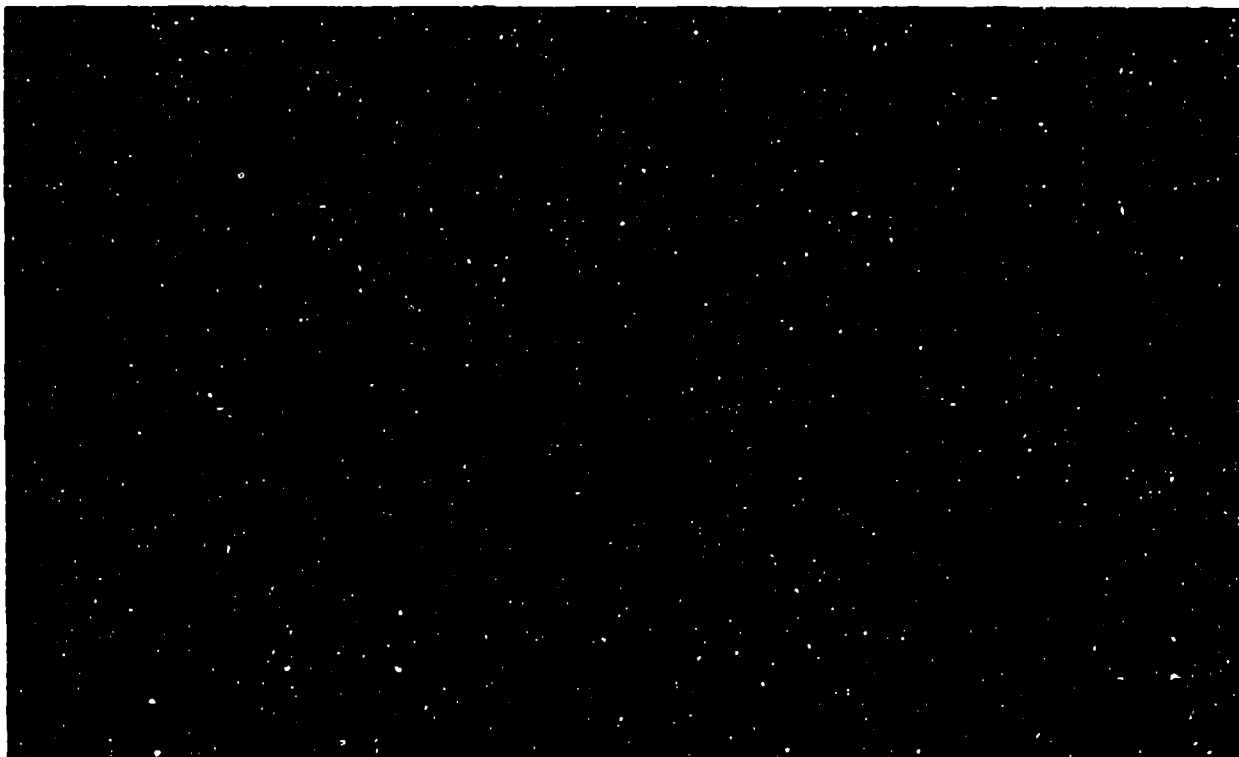


Figure 18. Effect of loss of peripheral visual orientation cues on perception of runway orientation during a black-hole approach. Above: When peripheral visual orientation cues are absent, pilot feels upright and (in this example) perceives runway to be tilted left and upsloping. Below: With horizon visible, pilot orients himself correctly with peripheral vision and runway appears horizontal in central vision.





Figure 19. A common and particularly dangerous type of black-hole approach, in which pilot perceives distant city to be flat and arcs below desired approach slope.

An approach made under whiteout conditions can be as difficult as a black-hole approach, and for essentially the same reason--lack of sufficient ambient visual orientation cues. There are actually two types of whiteout, the atmospheric whiteout and the blowing-snow whiteout. In the atmospheric whiteout, a snow-covered ground merges with a white overcast, creating a condition in which ground textural cues are absent and the horizon is indistinguishable. Although visibility may be unrestricted in the atmospheric whiteout, there is essentially nothing to see except the runway or runway markers; an approach made in this condition must therefore be accomplished with a close eye on the altitude and attitude instruments to prevent spatial disorientation and inadvertent ground contact. In the blowing-snow whiteout, visibility is restricted drastically by snowflakes, and often those snowflakes have been driven into the air by the propeller or rotor wash of the affected aircraft. Helicopter landings on snow-covered ground are particularly likely to create blowing-snow whiteout. Typically, the helicopter pilot tries to maintain visual contact with the ground

during the sudden rotor-induced whiteout, gets into an unrecognized drift to one side, and shortly thereafter contacts the ground with sufficient lateral motion to cause the craft to roll over. Pilots flying where whiteouts can occur must be made aware of the hazards of whiteout approaches, as the disorientation induced usually occurs unexpectedly under visual rather than instrument meteorologic conditions.

One puzzling illusion that occurs when visual orientation cues are minimal is visual autokinesis (Fig. 20) (21). A small, dim light seen against a dark background is an ideal stimulus for producing autokinesis. After 6 to 12 s of visually fixating the light, one can observe it to move at anywhere between 0.2 and 20 degrees/s, in one particular direction or in several directions in succession. Peripheral visual autokinesis is associated with smooth apparent movements and large apparent displacements, while central visual autokinesis is often saccadic or jerky, and results in little apparent displacement of the object fixated. In general, the larger the object and the brighter the object the less the autokinetic effect. The shape of the object seems to have little effect on the magnitude of the illusion, however. Nor does providing a larger number of objects necessarily reduce the illusory effect, as multiple objects can appear to move, either as a unit or independently, as vigorously as one alone. The physiologic mechanism of visual autokinesis is not understood; in fact, it is not even established with certainty whether actual eye movements are associated with autokinesis. One suggested explanation for the autokinetic phenomenon is that the eyes tend to drift involuntarily, perhaps because of inadequate or inappropriate vestibular stabilization, and checking the drift requires efferent oculomotor activity having sensory correlates that create the illusion.

Whatever the mechanism, the effect of visual autokinesis on pilots is of great importance. Anecdotes abound of pilots who fixate a star or a stationary ground light at night, and seeing it move because of autokinesis, mistake it for another aircraft and try to intercept or join up with it. Another untoward effect of the illusion occurs when a pilot flying at night perceives a relatively stable aircraft--one which he must intercept or follow--to be moving erratically, when in fact it is not; the unnecessary and undesirable control inputs the pilot makes to compensate for the illusory movement of the target aircraft represent increased work and wasted motion at best, and an operational hazard at worst.

To help avoid or reduce the autokinetic illusion, one should try to maintain a well-structured visual environment in which spatial orientation is unambiguous. Since this is rarely possible in night flying, it has been suggested that: (1) the gaze should be shifted frequently to avoid prolonged fixation of a target light; (2) the target should be viewed beside or through, and in reference to, a relatively stationary structure such as a canopy bow; (3) one should make eye, head, and body

movements to try to destroy the illusion; and (4) as always, one should monitor the flight instruments to help prevent or resolve any perceptual conflict. Equipping aircraft with more than one light or with luminescent strips to enhance recognition at night has probably helped reduce problems with autokinesis. It has not abolished them, however.

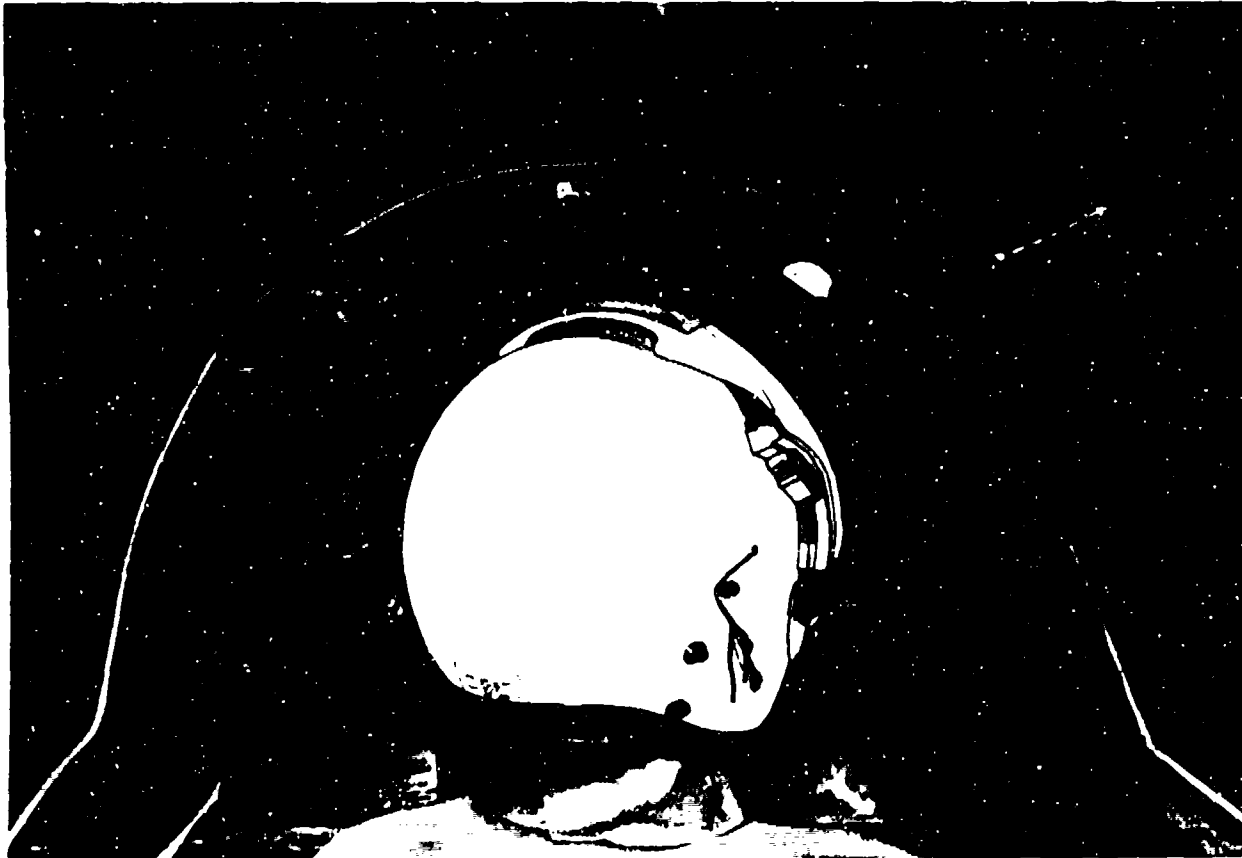


Figure 20. Visual autokinesis. A small, solitary light or small group of lights seen in the dark can appear to move, when in fact they are stationary.

So far we have discussed visual illusions created by excessive orientation-processing demands being placed on focal vision when adequate orientation cues are not available through ambient vision, or by strong but false orientation cues being received through focal vision. But ambient vision can itself be responsible for creating orientational illusions whenever orientation cues received in the visual periphery are misleading or misinterpreted. Probably the most compelling of such illusions are the vection illusions (4). Vection is the visually induced perception of motion of the self in the spatial environment

(self-motion), and can be a sensation of linear motion (linear vection) or angular motion (angular vection).

Nearly everyone who drives an automobile has experienced one very common linear vection illusion: when a driver is waiting in his car at a stop light and a presumably stationary bus or truck in the adjacent lane creeps forward, a compelling illusion that his own car is creeping backward can result (prompting a swift but surprisingly ineffectual stomp on the brake). Another example is that of a passenger sitting in a stationary train when the train on the adjacent track begins to move: he can experience the strong sensation that his own train is moving in the opposite direction (Fig. 21a). Linear vection is one of the factors that make close formation flying so difficult, as the pilot can never be sure whether his own aircraft or that of his lead or wingman is responsible for the relative motion of his aircraft.

Angular vection occurs when peripheral visual cues convey the information that one is rotating; and the perceived rotation can be in pitch, roll, yaw, or any other plane. Although angular vection illusions are not common in everyday life, they can be generated readily in a laboratory by enclosing a stationary subject in a rotating striped drum. Usually within 10 s after the visual motion begins, the subject perceives that he, rather than the striped drum, is rotating. A pilot can experience angular vection if the rotating anticollision light on his aircraft is left on during flight through clouds or fog: the revolving reflection provides a strong ambient visual stimulus signalling rotation in the yaw plane. Another condition resulting in angular vection is that in which a just-activated landing light rotates forward under the wing or nose, casting an upward-moving area of illumination in the surrounding fog or cloud, possibly even creating a rising false horizon. As a result of the illusory pitch vection generated, the pilot could be tempted to raise the nose of the aircraft at a most inappropriate time.

Fortunately, the vection illusions are not all bad. The most advanced flight simulators depend on linear and angular vection to create the illusion of flight (Fig. 21b). When the visual flight environment is dynamically portrayed in wide-field-of-view flight simulators, the illusion of actual flight is so complete and compelling that additional mechanical motion is rendered superfluous.

Another result of false ambient visual orientational cueing is the lean-on-the-sun illusion. On the ground, we are accustomed to seeing the brighter visual surround above and the darker below, regardless of the position of the sun. The direction of this gradient in light intensity thus helps us orient with respect to the surface of the earth. In cloud, however, such a gradient usually does not exist; and when it does, the lighter direction is generally toward the sun and the

darker away from it. But the sun is almost never directly overhead; as a consequence, a pilot flying in a thin cloud layer tends to perceive falsely the direction of the sun as directly overhead, and to align his aircraft accordingly. This misperception causes him to bank in the direction of the sun--whence the name of the illusion. A variant of this phenomenon involves a somewhat different mechanism: sometimes a pilot remembers the relative bearing of the sun when he first penetrated the weather, and he unconsciously tries to keep the sun in the same relative position whenever it peeks through the cloud. On a prolonged flight in intermittent weather, the changing position of the sun in the sky can cause the pilot to become mildly confused and fly his aircraft with less precision than he would in either continuously visual or continuously instrument meteorologic conditions.

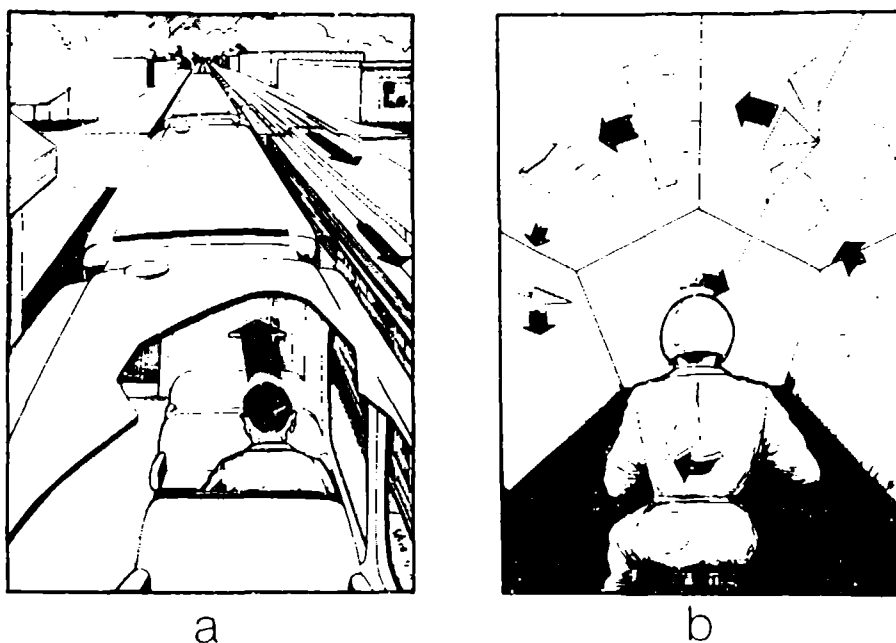


Figure 21. Vection illusions. a. Linear vection. In this example, adjacent vehicle seen moving aft in subject's peripheral vision causes him to feel he is moving forward. b. Angular vection. Visually perceived objects revolving around subject in flight simulator cause him to sense self-rotation in opposite direction--in this case a rolling motion to the right.

Often the horizon perceived through ambient vision is not really horizontal. Quite naturally, this misperception of the horizontal creates hazards to flight. A sloping cloud deck, for example, is very difficult to perceive as anything but horizontal if it extends for any great distance in the pilot's peripheral vision (Fig. 22). Uniformly sloping terrain can also create an

illusion of horizontality, with disastrous consequences for the pilot thus deceived. Many aircraft have crashed as a result of the pilot's entering a canyon with an apparently level floor that actually rises faster than the airplane can climb; the pilot arrives at the end of the canyon "out of altitude, air-speed, and ideas," as they say. Sometimes a distant rain shower can obscure the real horizon and create the impression of a horizon at the proximal edge (base) of the rainfall. If the shower is seen just beyond the runway during an approach to landing, the pilot can misjudge the pitch attitude of his aircraft and make inappropriate pitch corrections on the approach.



Figure 22. A sloping cloud deck, which the pilot misperceives as a horizontal surface.

Pilots are especially susceptible to misperception of the horizontal when flying at night (Fig. 23). Isolated ground lights can appear to the pilot to be stars, causing him to think he is in a nose-high or one-wing-low attitude. Correcting for such a false impression can, of course, be fatal. Frequently no stars are visible because of an overcast. Unlighted areas of terrain can then blend with the dark overcast to create the illusion that the unlighted terrain is part of the sky. One

extremely hazardous situation is that in which a takeoff is made over an ocean or other large body of water that cannot be distinguished visually from the night sky. Many pilots in this situation have perceived the shoreline receding beneath them to be the horizon and some have reacted to this false percept with disastrous consequences.

Pilots flying at very high altitudes can sometimes experience difficulties with control of aircraft attitude, because at high altitudes the horizon is lower with respect to the plane of level flight than it is at the lower altitudes where most pilots usually fly. As a reasonable approximation, the angle of depression of the horizon in degrees equals the square root of the altitude in kilometers. A pilot flying at an altitude of 15 km thus sees the horizon almost 4 degrees below the extension of his horizontal plane. If he visually orients to the view from his left cockpit window, he might be inclined to fly with the left wing 4 degrees down to level it with the horizon. If he does this, and then looks out his right window, he would see the right wing 8 degrees above the horizon, with half of that elevation due to his own erroneous control input. He might also experience problems with pitch control, as the depressed horizon can cause him to perceive falsely a 4-degree nose-high pitch attitude.

Finally, the disorienting effects of the northern lights and of aerial flares should be mentioned. Aerial refueling at night in high northern latitudes is often made quite difficult by the northern lights, which provide false cues of verticality to the pilot's peripheral vision. In addition, the movement of the auroral display may make the pilot susceptible tovection illusions. Similarly, when aerial flares are dropped, they may descend vertically--or they may drift with the wind, creating false cues of verticality. Their motion may also createvection illusions. An important additional factor is that the aurora and aerial flares can be so bright as to reduce the apparent intensity, and therefore the orientational cueing strength, of the aircraft instrument displays.

Vestibular Illusions. The vestibulocerebellar axis processes orientation information from the vestibular end-organs, the nonvestibular proprioceptors, and the peripheral visual fields. In the absence of adequate ambient visual orientation cues, the inadequacies of the vestibular and other orienting senses can, and generally do, result in orientational illusions. It is convenient and conventional to discuss the vestibular illusions in relation to the two labyrinthine components that generate them--the semicircular ducts and the otolith organs.

The somatogyral illusion results from the inability of the semicircular ducts to register accurately a prolonged rotation, i.e., sustained angular velocity. When a person is subjected to an angular acceleration about the yaw axis, for example, the angular motion is at first perceived accurately, because the dynamics of the cupula-endolymph system cause it to respond as

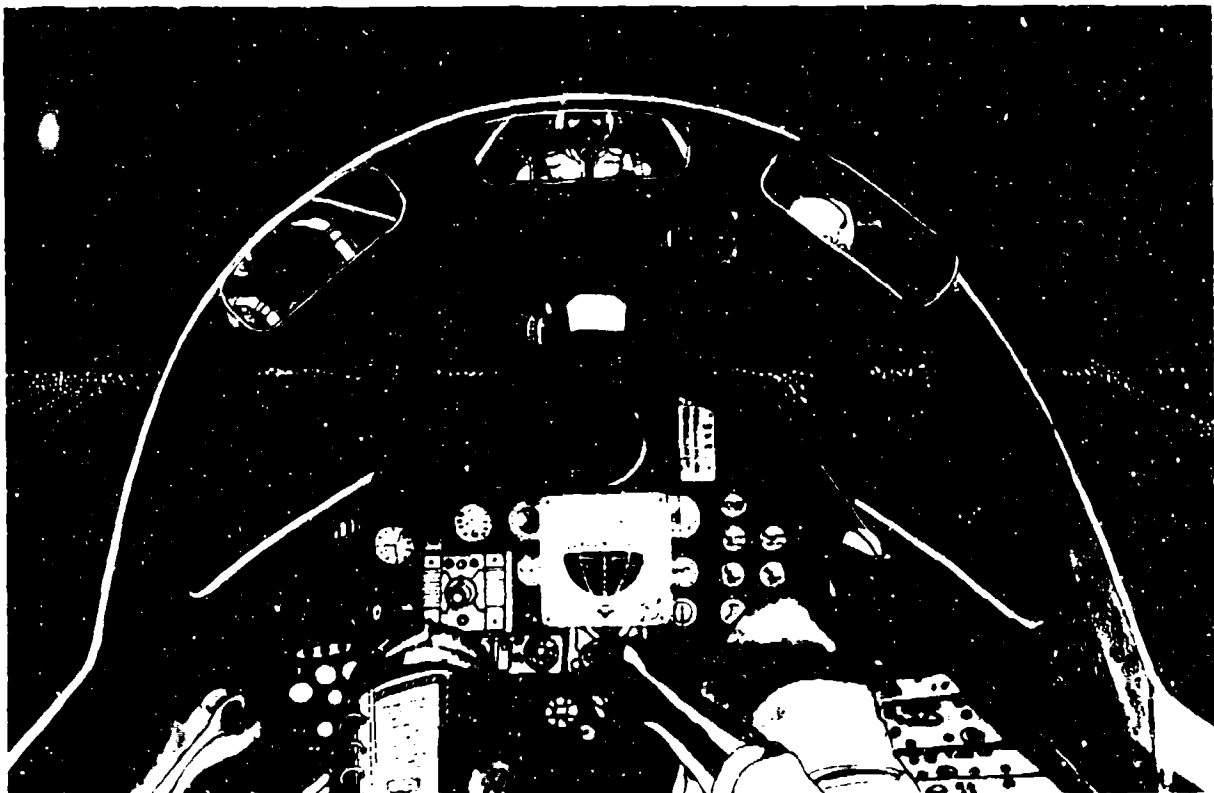
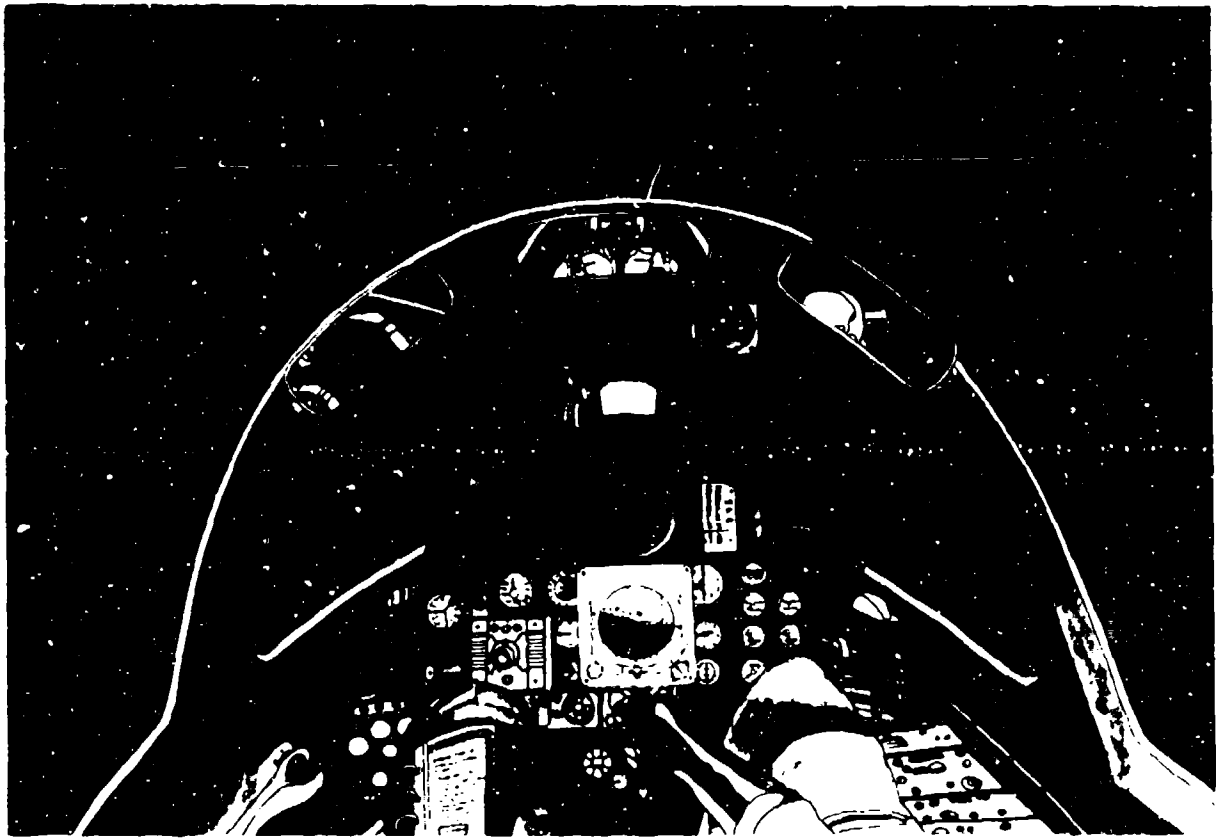


Figure 23. Misperception of the horizontal at night. Above: Ground lights appearing to be stars cause earth and sky to blend and a false horizon to be perceived. Below: Blending of overcast sky with unlighted terrain or water causes horizon to appear lower than is actually the case.

an integrating angular accelerometer (i.e., as a rotation rate sensor) at stimulus frequencies in the physiologic range (Fig. 24). If the acceleration is followed immediately by a deceleration, as usually happens in the terrestrial environment, the total sensation of turning one way and then stopping the turn is quite accurate (Fig. 25). But if the angular acceleration is not followed by a deceleration, and a constant angular velocity results instead, the sensation of rotation becomes less and less and eventually disappears as the cupula gradually returns to its resting position in the absence of an angular acceleratory stimulus (Figs. 25, 26). If the rotating subject is subsequently subjected to an angular deceleration after a period of prolonged constant angular velocity--say, after 10 s or more of constant-rate turning--his cupula-endolymph system then signals a turn in the direction opposite that of the prolonged constant angular velocity, even though he is really only turning less rapidly in the same direction. This sensory response occurs because the angular momentum of the rotating endolymph causes it to press against the cupula, forcing the cupula to deviate in the direction of endolymph flow, which is the same direction the cupula would deviate if the subject were to accelerate in the direction opposite his initial acceleration. Even after rotation actually ceases, the sensation of rotation in the direction opposite that of the sustained angular velocity persists for several seconds--half a minute or longer with a large decelerating rotational impulse. Technically speaking, a somatogyral illusion is the sensation of turning in the opposite direction that occurs whenever one undergoes angular deceleration from a condition of constant angular velocity. It is practical, however, to include in this category of illusions the sensation of turning more slowly and eventually ceasing to turn while angular velocity persists, because the two illusions have a common underlying mechanism and they inevitably occur in pairs. An even broader definition of somatogyral illusion is "any discrepancy between actual and perceived rate of self-rotation that results from an abnormal angular acceleratory stimulus pattern." The term "abnormal" in this case implies the application of low-frequency stimuli, outside the useful portion of the transfer characteristics of the semicircular duct system.

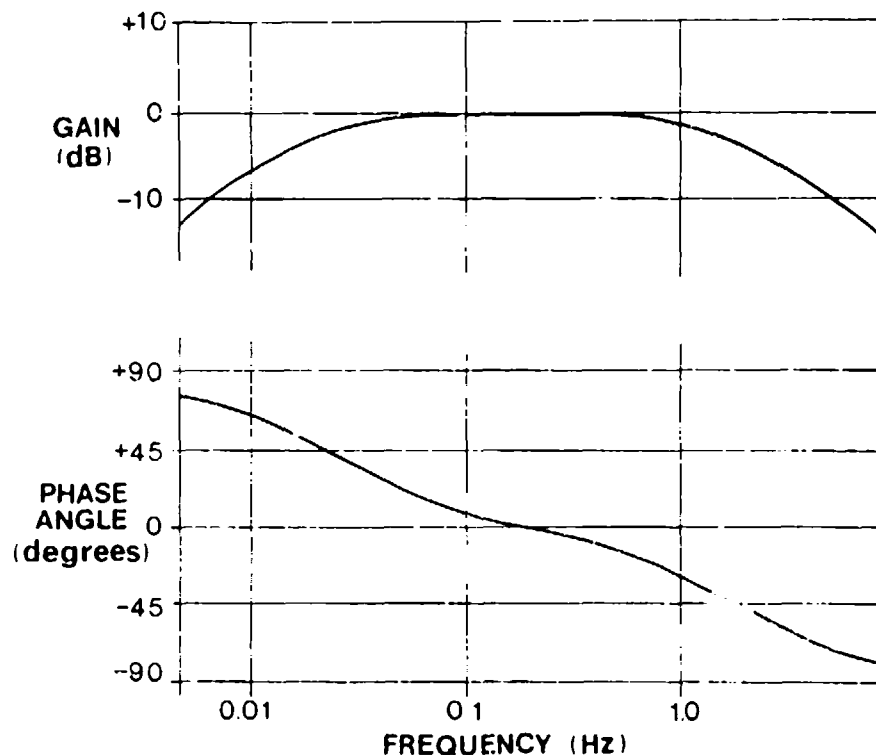


Figure 24. Transfer characteristics of the semicircular duct system as a function of sinusoidal stimulus frequency. Gain is the ratio of the magnitude of peak perceived angular velocity to peak delivered angular velocity; phase angle is a measure of the amount of advance or delay between peak perceived and peak delivered angular velocity. Note that in the physiologic frequency range (roughly 0.05 to 1 Hz), perception is accurate; i.e., gain is close to unity (0 dB) and phase shift is minimal. At lower stimulus frequencies, however, the gain drops off rapidly and the phase shift approaches 90 degrees, which means that angular velocity becomes difficult to detect and that angular acceleration is perceived as velocity. (Adapted from Peters (23).)

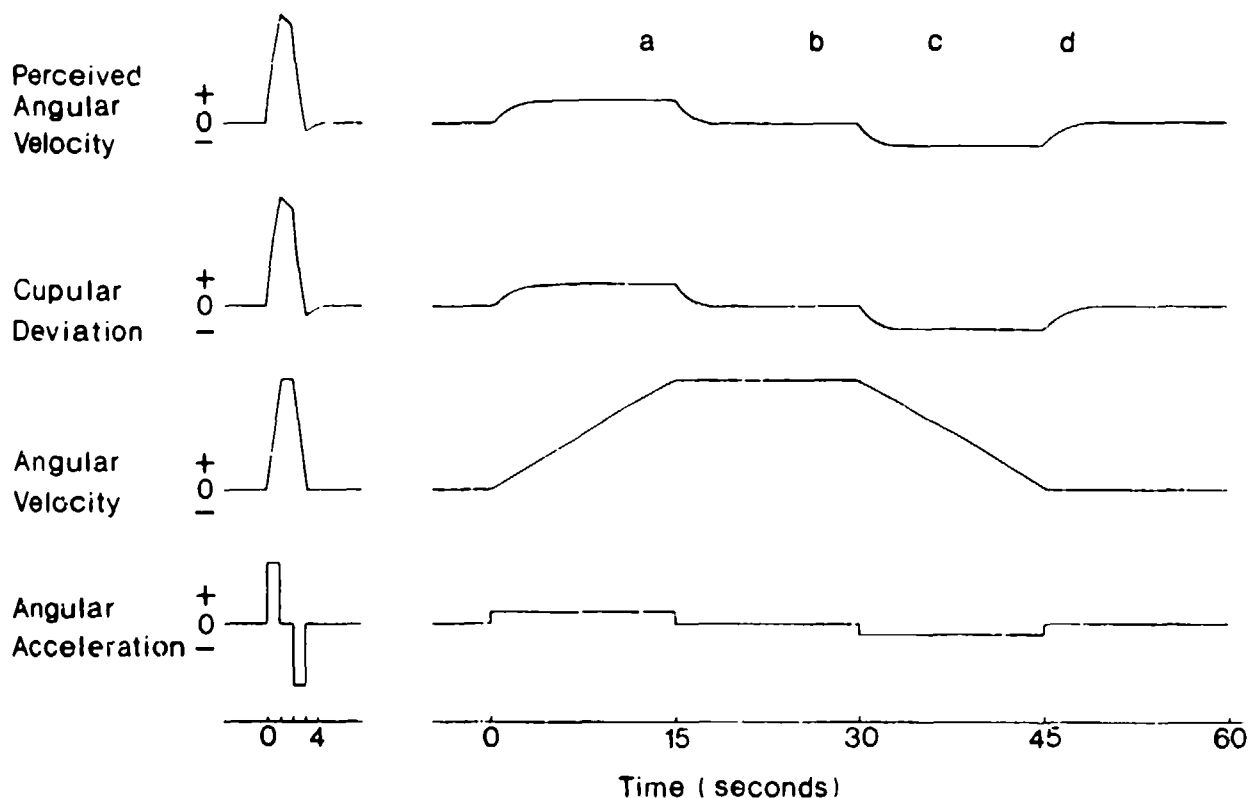


Figure 25. Effect of stimulus pattern on perception of angular velocity. On the left, the high-frequency character of the applied angular acceleration results in a cupular deviation that is nearly proportional, and perceived angular velocity that is nearly identical, to the angular velocity developed. On the right, the peak angular velocity developed is the same as that on the left, but the low-frequency character of the applied acceleration results in cupular deviation and perceived angular velocity that appear more like the applied acceleration than the resulting velocity. This causes one to perceive: (a) less than the full amount of the angular velocity, (b) that he is not turning when he actually is, (c) a turn in the opposite direction from that of the actual turn, (d) that turning persists after it has actually stopped. These false perceptions are somatogyral illusions.

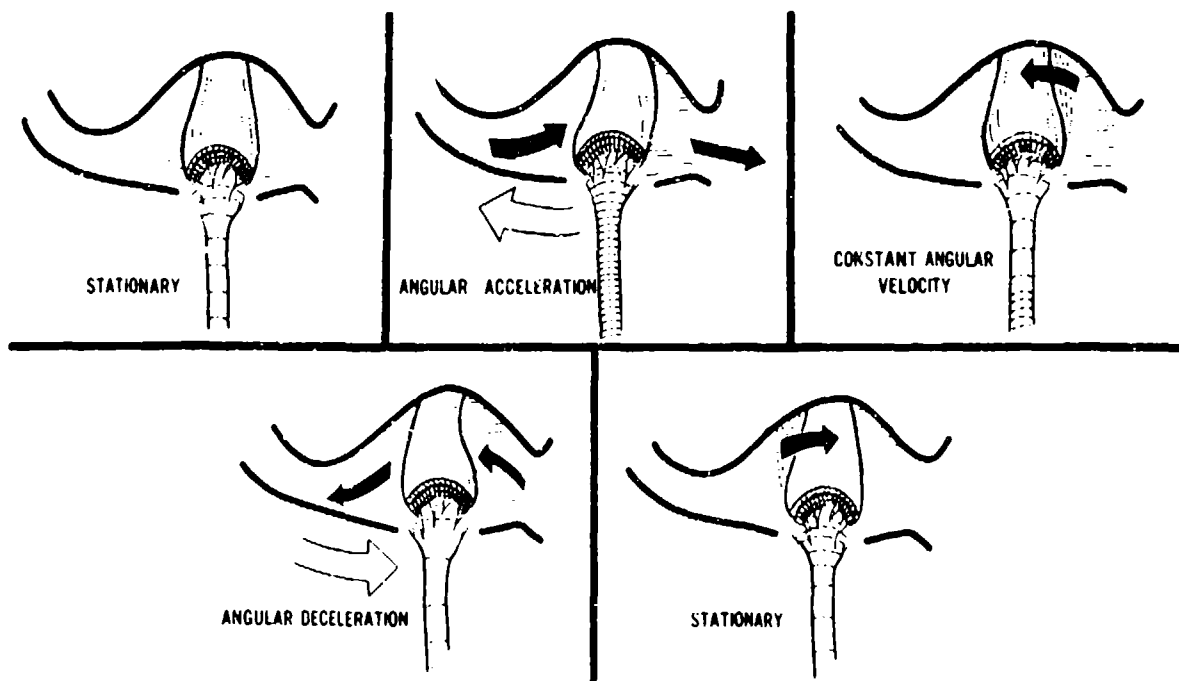


Figure 26. Pictorial representation of mechanical events occurring in a semicircular duct and resulting action potentials in associated ampullary nerve during somatogyral illusions. Angular acceleration pattern applied is shown in right side of Figure 25.

In flight under conditions of reduced visibility (night or instrument weather), somatogyral illusions can be deadly. The graveyard spin is the classic example of how somatogyral illusions can disorient a pilot, with fatal results. This situation begins with the pilot intentionally or unintentionally entering a spin, let's say to the left (Fig. 27). At first the pilot perceives the spin correctly, as the angular acceleration associated with entering the spin deviates the appropriate cupulae the appropriate amount in the appropriate direction. The longer the spin persists, however, the more the sensation of spinning to the left diminishes as the cupulae return to their resting positions. If the pilot tries to stop the spin to the left by applying right rudder, the angular deceleration causes him to perceive a spin to the right, even though the only real result of his action is termination of the spin to the left. A pilot who is ignorant of the possibility of such an illusion is then likely to make counterproductive left rudder inputs to negate the unwanted erroneous sensation of spinning to the right. These inputs keep the airplane spinning to the left, which gives the pilot the desired sensation of not spinning but does not bring the airplane under control. To extricate himself from this very hazardous situation the pilot must read the aircraft flight instruments and apply control inputs to make the

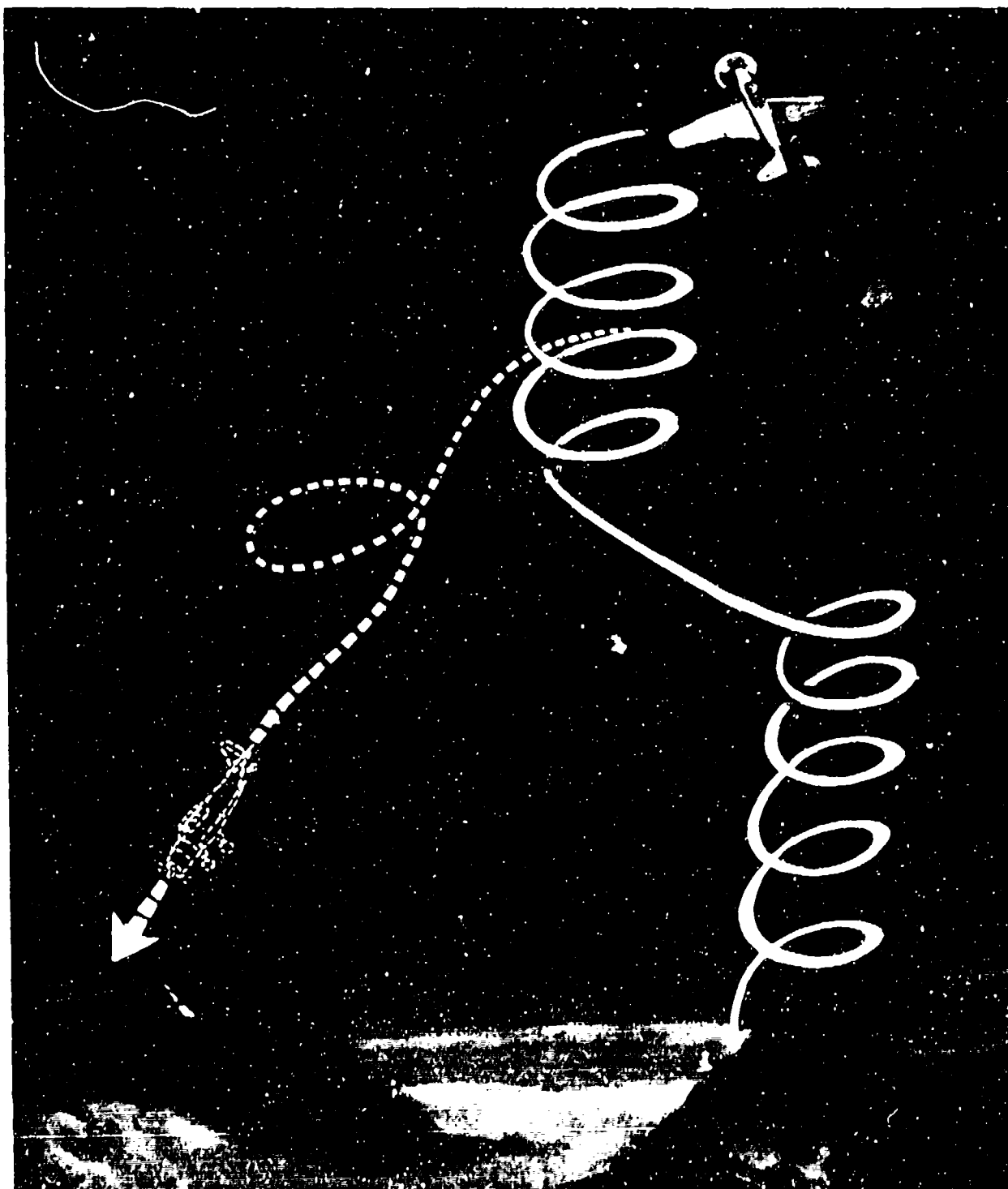
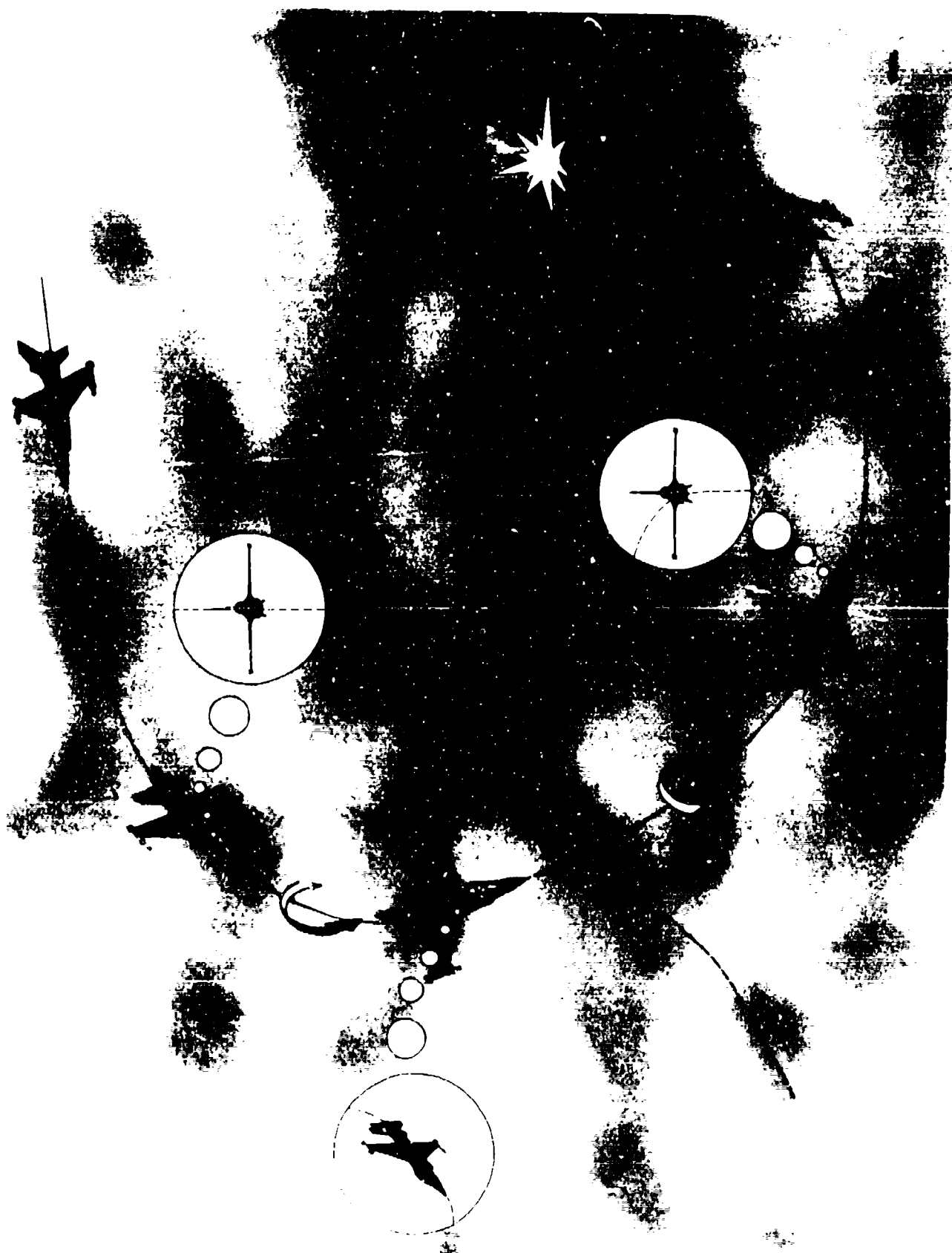


Figure 27. The graveyard spin. After several turns of a spin the pilot begins to lose the sensation of spinning. Then when he tries to stop the spin, the resulting somatogyral illusion of spinning in the opposite direction makes him reenter the original spin. (Solid line indicates actual motion; dotted line indicates perceived motion.)

instruments give the desired readings (push right rudder to center the turn needle, in this example). Unfortunately, this may not be so easy to do. The angular accelerations created by both the multiple-turn spin and the pilot's spin-recovery attempts can elicit strong but inappropriate vestibulo-ocular reflexes, including nystagmus. In the usual terrestrial environment these reflexes help stabilize the retinal image of the visual surround; but in this situation they only destabilize it, because the visual surround (cockpit) is already fixed with respect to the pilot. Reading the flight instruments thus becomes difficult or impossible in this situation, and the pilot is left with only his false sensations of rotation to rely on for spatial orientation and aircraft control (24).

While the lore of early aviation provided the graveyard spin as an illustration of the hazardous nature of somatogyral illusions, a much more common example occurring all too often in present-day aviation is the graveyard spiral (Fig. 28). In this situation the pilot has intentionally or unintentionally gotten himself into a prolonged turn with a moderate amount of bank. After a number of seconds in the turn the pilot loses the sensation of turning because his cupula-endolymph system cannot respond to constant angular velocity. The percept of being in a bank as a result of the initial roll into the banked attitude also decays with time, because the net gravito-inertial force vector points toward the floor of the aircraft during coordinated flight (whether the aircraft is in a banked turn or flying straight and level) and the otolith organs and other graviceptors normally signal that down is in the direction of the net sustained gravito-inertial force. As a result, when the pilot tries to stop the turn by rolling back to a wings-level attitude, he not only feels he is turning in the direction opposite that of

Figure 28. The graveyard spiral. The pilot in a banked turn loses the sensation of being banked and turning. Upon trying to reestablish a wings-level attitude and stop the turn, he perceives that he is banked and turning in the opposite direction from his original banked turn; i.e., he experiences a somatogyral illusion. Unable to tolerate the sensation that he is making an inappropriate control input, the pilot banks back into the original turn.



his original turn, but also feels he is banked in the direction opposite that of his original bank. Unwilling to accept this sensation of making the wrong control input, the hapless pilot rolls back into his original banked turn. Now his sensation is compatible with his desired mode of flight, but his instruments say he is losing altitude (because the banked turn is wasting lift) and still turning. So he pulls back on the stick and perhaps adds power to arrest the unwanted descent and regain the lost altitude. This action would be successful if the aircraft were flying wings-level, but with the aircraft in a banked attitude it tightens the turn, serving only to make matters worse. Unless the pilot eventually recognizes his error and rolls out of his unperceived banked turn, he will continue to descend in an ever-tightening spiral toward the ground--whence the name, graveyard spiral.

Whereas a somatogyral illusion is a false sensation, or lack of sensation, of self-rotation in a subject undergoing unusual angular motion, an oculogyral illusion is a false sensation of motion of an object viewed by such a subject (25). For example: if a vehicle with a subject inside is rotating about a vertical axis at a constant velocity and suddenly stops rotating, the subject experiences not only a somatogyral illusion of himself rotating in the opposite direction, but also an oculogyral illusion of an object in front of him moving in the opposite direction. Thus, a somewhat oversimplified definition of the oculogyral illusion is that it is the visual correlate of the somatogyral illusion; but its very low threshold and its lack of total correspondence with presumed cupular deviation suggest a more complex mechanism. The attempt to maintain visual fixation during a vestibulo-ocular reflex elicited by angular acceleration is probably at least partially responsible for the oculogyral illusion. (A similar mechanism underlies the illusory movement of the moon when one tries to fixate it visually while the relative movement of surrounding clouds is eliciting an optokinetic tracking reflex.) In an aircraft during flight at night or in weather an oculogyral illusion generally confirms a somatogyral illusion: the pilot who falsely perceives that he is turning in a particular direction also observes his instrument panel to be moving in the same direction.

The vestibular Coriolis effect, Coriolis cross-coupling effect, vestibular cross-coupling effect, or simply the Coriolis illusion, is another false percept that can result from unusual stimulation of the semicircular duct system. To illustrate this phenomenon, let us consider a subject who has been rotating in the plane of his horizontal semicircular ducts (roughly the yaw plane) long enough for the endolymph in those ducts to attain the same angular velocity as his head: the cupulae in the ampullae of his horizontal ducts have returned to their resting positions, and the sensation of rotation has ceased (Fig. 29a). If the subject then nods his head forward in the pitch plane, let's say a full 90 degrees for the sake of simplicity, he is

completely removing his horizontal semicircular ducts from the plane of rotation and inserting his two sets of vertical semicircular ducts into the plane of rotation (Fig. 29b). While the angular momentum of the subject's rotating head is forcibly transferred at once out of the old plane of rotation relative to his head, the angular momentum of the endolymph in the horizontal duct is dissipated more gradually. The torque resulting from the continuing rotation of the endolymph causes the cupulae in the horizontal ducts to be deviated, and a sensation of angular motion occurs in the new plane of the horizontal ducts--now the roll plane relative to the subject's body. Simultaneously, the endolymph in the two sets of vertical semicircular ducts must acquire angular momentum, as these ducts have been brought into the plane of constant rotation. The torque required to impart this change in momentum causes deflection of the cupulae in the ampullae of these ducts, and a sensation of angular motion in this plane--the yaw plane relative to the subject's body--is the result. The combined effect of the cupular deflection in all three sets of semicircular ducts is that of a suddenly imposed angular velocity in a plane in which no actual angular acceleration relative to the subject has occurred. In the example given, if the original constant-velocity yaw is to the right and the subject pitches his head forward, the resulting Coriolis illusion experienced is that he and his immediate surroundings are suddenly rolling to the right and yawing to the right.

A particular perceptual phenomenon experienced occasionally by pilots of relatively high-performance aircraft during instrument flight has been attributed to the Coriolis illusion because it occurs in conjunction with large movements of the head under conditions of prolonged constant angular velocity. It consists of a very convincing sensation of rolling and/or pitching that appears suddenly after the pilot diverts his attention from the instruments in front of him and moves his head to view some switches or displays elsewhere in the cockpit. This illusion is especially deadly because it is most likely to occur during an instrument approach, a phase of flight in which altitude is being lost rapidly and cockpit chores (e.g., radio frequency changes) repeatedly require the pilot to break up his instrument cross-check. Whether the sustained angular velocities associated with instrument flying are sufficient to create Coriolis illusions of any great magnitude is debatable, however (26); and another mechanism (the G-excess effect) has been proposed to explain the illusory rotations experienced with head movements in flight. Even if not responsible for spatial disorientation in flight, the Coriolis illusion is useful as a tool to demonstrate the fallibility of our nonvisual orientation senses. Nearly every military pilot living today has experienced the Coriolis illusion in the Barany chair or some other rotating device as part of his physiological training; and for most of them it was then that they first realized their own orientation senses really cannot be trusted--the most important lesson of all for instrument flying.

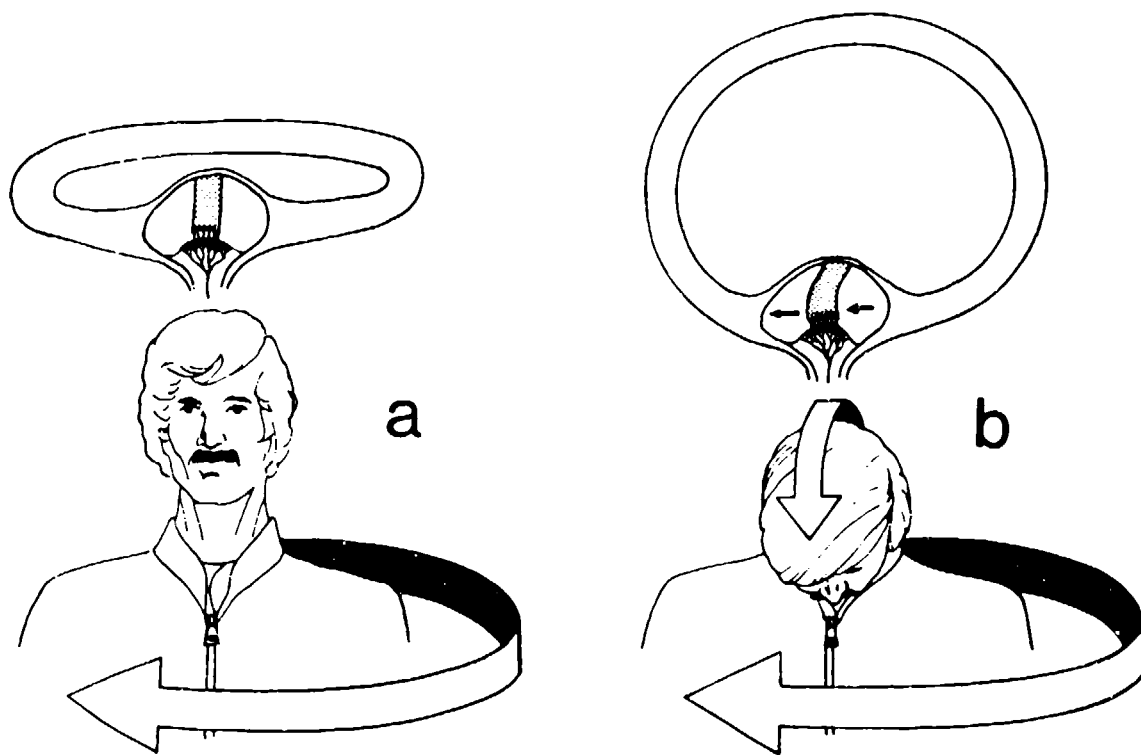


Figure 29. Mechanism of the Coriolis illusion. Subject rotating in yaw plane long enough for endolymph to stabilize in semicircular duct (a), pitches head forward (b). Angular momentum of endolymph deviates cupula, causing subject to perceive rotation in new plane of semicircular duct, even though no actual rotation occurred in that plane.

The otolith organs are responsible for a set of illusions known as somatogravic illusions. The mechanism of illusions of this type involves the displacement of otolithic membranes on their maculae by inertial forces in such a way as to signal a false orientation when the resultant gravitoirertial force is perceived as gravitational (and therefore vertical). The paragon of somatogravic illusions, the illusion of pitching up after taking off into conditions of reduced visibility, is perhaps the best illustration of this mechanism. Consider the pilot of a high-performance aircraft holding his position at the end of the runway waiting to take off. Here the only force acting on his otolithic membranes is the force of gravity, and the positions of those membranes on their maculae signal accurately that down is toward the floor of the aircraft. Suppose the aircraft now accelerates down the runway, rotates, takes off, cleans up gear and flaps, and maintains a forward acceleration of 1 g until reaching desired climb speed. The 1 G of inertial force resulting from the forward acceleration displaces the otolithic membranes toward the back of the pilot's head. In

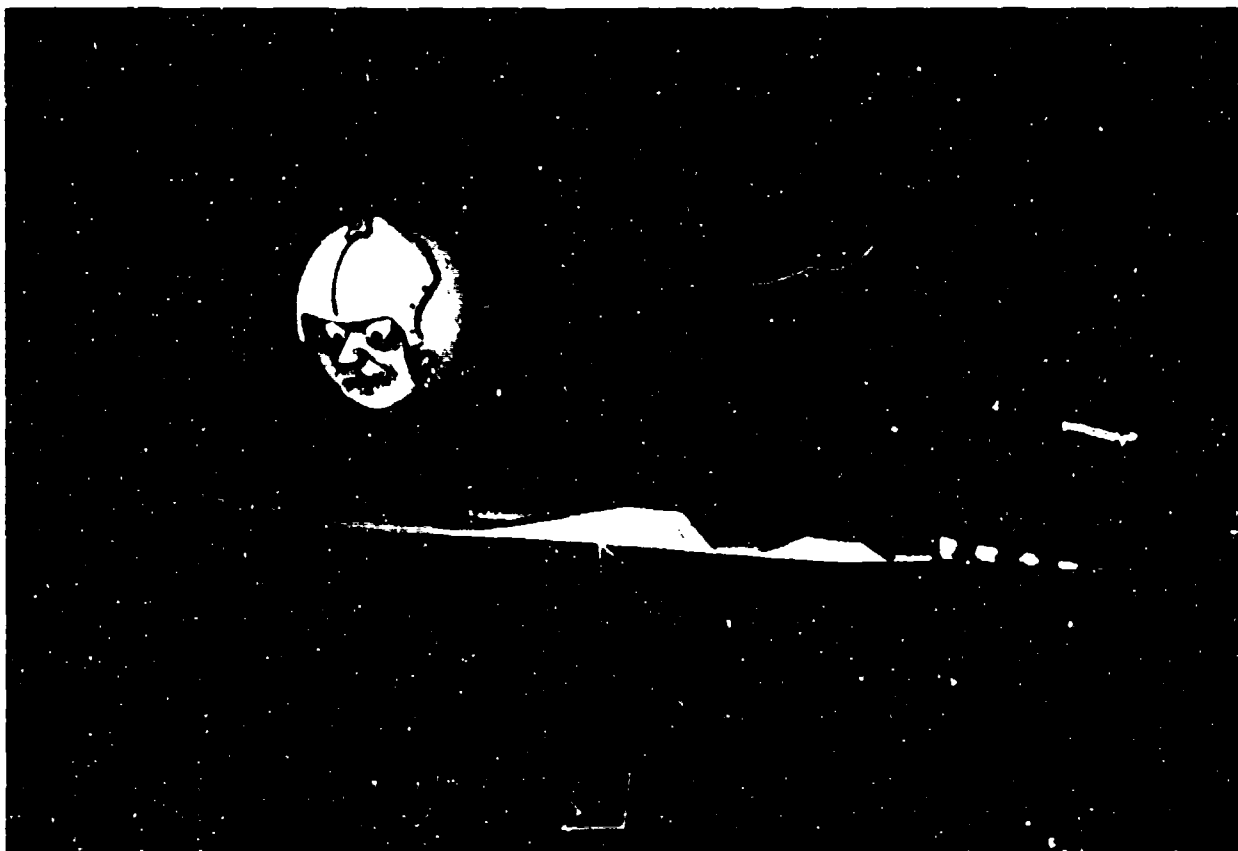


Figure 30. A somatogravic illusion occurring on takeoff. The inertial force resulting from the forward acceleration combines with the force of gravity to create a resultant gravito-inertial force directed down and aft. The pilot, perceiving down to be in the direction of the resultant gravito-inertial force, feels he is in an excessively nose-high attitude, and is tempted to push the stick forward to correct the illusory nose-high attitude.

fact, the new positions of the otolithic membranes are nearly the same as they would be if the aircraft and pilot had pitched up 45 degrees, since the new direction of the resultant gravito-inertial force vector (if we neglect the angle of attack and climb angle) is 45 degrees aft relative to the gravitational vertical (Fig. 30). Naturally, the pilot's percept of pitch attitude based on the information from his otolith organs is one of having pitched up 45 degrees; and the information from his nonvestibular proprioceptive and cutaneous mechanoreceptive senses supports this false percept, as the sense organs subserving those modalities also respond to the direction and intensity of the resultant gravito-inertial force. Given the very strong sensation of a nose-high pitch attitude, one that is not challenged effectively by the focal visual orientation cues provided

by the attitude indicator, the pilot is tempted to push the nose of the aircraft down to cancel the unwanted sensation of flying nose-high. Pilots succumbing to this temptation characteristically crash in a nose-low attitude a few miles beyond the end of the runway. Sometimes, however, they are seen to descend out of the overcast nose-low and to try belatedly to pull up, as though they suddenly regained the correct orientation upon seeing the ground again. Pilots of carrier-launched aircraft need to be especially wary of the somatogravic illusion. These pilots experience pulse accelerations lasting 2 to 4 s and generating peak inertial forces of +3 to +5 G_x . Although the major acceleration is over rather quickly, the resulting illusion of nose-high pitch can persist for half a minute or more afterwards, resulting in a particularly hazardous situation for the pilot who is unaware of this phenomenon (27).

Pilots of high-performance aircraft are not the only ones to suffer the somatogravic illusion of pitching up after takeoff. More than a dozen air transport aircraft are believed to have crashed as a result of pilots' experiencing the somatogravic illusion on takeoff (28). A relatively slow aircraft, accelerating from 100 to 130 knots over a 10-s period just after takeoff, generates +0.16 G_x on the pilot. Although the resultant gravito-inertial force is only 1.01 G, barely perceptibly more than the force of gravity, it is directed 9 degrees aft, signifying to the unwary pilot a 9-degree nose-up pitch attitude. As many slower aircraft climb out at 6 degrees or less, a 9-degree downward pitch correction would put such an aircraft into a descent of 3 degrees or more--the same as a normal final-approach slope. In the absence of a distinct external visual horizon--even worse, in the presence of a false visual horizon (e.g., a shoreline) receding under the aircraft and reinforcing the vestibular illusion--the pilot's temptation to push the nose down can be overwhelming. This type of mishap has happened at one particular civil airport so often that a notice has been placed on navigational charts cautioning pilots flying from this airport to be aware of the potential for loss of attitude reference.

Although the classic graveyard spiral was earlier indicated to be a consequence of the pilot's suffering a somatogyral illusion, it can also be considered to result from a somatogravic illusion. A pilot who is flying "by the seat of his pants" applies the necessary control inputs to create a resultant G-force vector having the same magnitude and direction as that which his desired flight path would create. Unfortunately, any particular G vector is not unique to one particular condition of aircraft attitude and motion; and the likelihood that the G vector created by a pilot flying without reference to instruments is that of the flight condition desired is remote indeed. Specifically, once an aircraft has departed a desired wings-level attitude because of an unperceived roll, and the pilot does not correct the resulting bank, the only way he can create a G vector which matches that of the straight and level condition is

with a descending spiral. In this condition, as is always the case in a coordinated turn, the centrifugal force resulting from the turn provides a G_y force which cancels the G_y component of the force of gravity that exists when the aircraft is banked. In addition, the tangential linear acceleration associated with the increasing airspeed resulting from the dive provides a $+G_x$ force which cancels the $-G_x$ component of the gravity vector that exists when the nose of the aircraft is pointed downward. Although the vector analysis of the forces involved in the graveyard spiral is somewhat complicated, a pilot can easily and automatically manipulate the stick and rudder pedals to cancel all vestibular and other nonvisual sensory indications that his aircraft is turning and diving. In one mishap involving a dark-night takeoff of a commercial airliner, the recorded flight data indicated that the resultant G force which the pilot created by his control inputs allowed him to perceive his desired 10- to 12-degree climb angle, and a net G force between 0.9 and 1.1 G, for virtually the whole flight--even though he actually levelled off and then descended in an accelerating spiral until the aircraft crashed nearly inverted (Fig. 31).

The inversion illusion is a type of somatogravic illusion in which the resultant gravito-inertial force vector rotates so far backward as to be pointing away from, rather than toward, the earth's surface, thus giving the subject of this phenomenon the false sensation that he is upside down. Figure 32 shows how this can happen. Typically, a steeply climbing high-performance aircraft levels off more or less abruptly at the desired altitude. This maneuver subjects the aircraft and pilot to a $-G_z$ centrifugal force resulting from the arc flown just prior to level-off. Simultaneously, as the aircraft changes to a more level attitude, airspeed picks up rapidly, adding a $+G_x$ tangential inertial force to the overall force environment. Adding the $-G_z$ centrifugal force and the $+G_x$ tangential force to the 1-G gravitational force results in a net gravito-inertial force vector that rotates backward and upward relative to the pilot. This stimulates his otolith organs in a manner similar to the way a pitch upward into an inverted position would. Even though the semicircular ducts should respond to the actual pitch downward, for some reason this conflict is resolved in favor of the otolith-organ information--perhaps because the semicircular duct response is transient while the otolith-organ response persists, or perhaps because the information from the nonvestibular proprioceptors and other mechanoreceptors reinforces that from the otolith organs. The pilot who responds to the inversion illusion by pushing forward on the stick to counter the perceived pitching up and over backward only prolongs the illusion by creating more $-G_z$ and $+G_x$ forces, thus aggravating his situation. Turbulent weather usually contributes to the development of the illusion; certainly, downdrafts are a source of $-G_z$ forces that can add to the net gravito-inertial force producing the inversion illusion. Again, one does not have to be flying a jet fighter to experience this illusion. A number of reports of the inversion illusion describe the loss of control of air transport

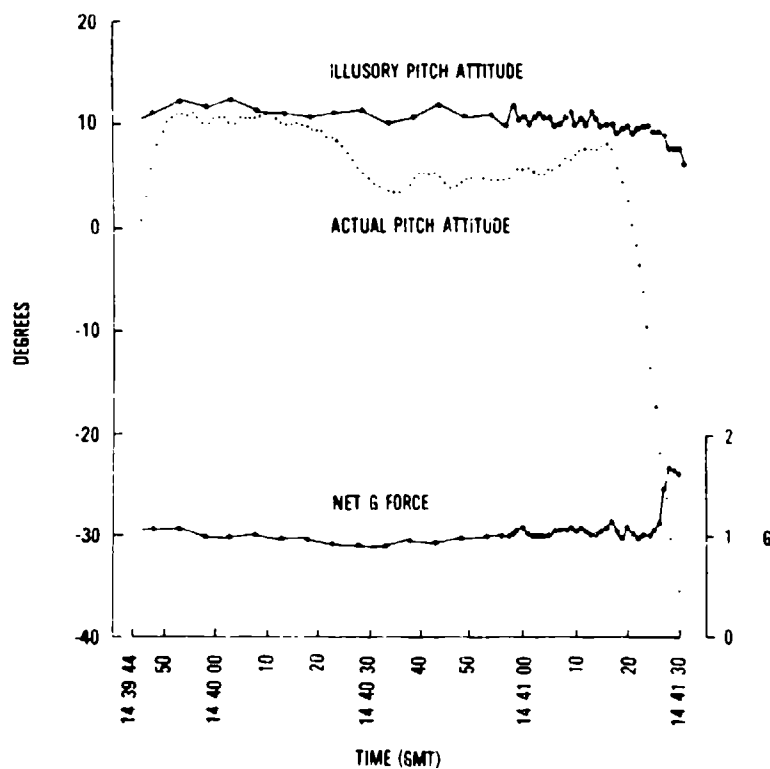


Figure 31. Flight recorder data from a wide-body jetliner that crashed less than two minutes after taking off over the ocean on a dark night. Although the net gravito-inertial force was essentially 1.0 G directed 10 to 12 degrees aft of the aircraft vertical through nearly the whole flight, the aircraft actually leveled off and eventually entered a spiral dive into the water. The fact that the desired flight profile (a straight climb) would have yielded the same gravito-inertial force environment as was actually generated is strong evidence that the pilot was spatially disoriented.

aircraft that occurred when the pilot lowered the nose inappropriately after experiencing the illusion. Jet upset is the term for the sequence of events that includes instrument weather, turbulence, inability of the pilot to read his instruments, the inversion illusion, a pitch-down control input, and difficulty recovering the aircraft because of resulting aerodynamic or mechanical forces (30).



Figure 32. The inversion illusion. Centrifugal and tangential inertial forces during a level-off combine with the force of gravity to produce a resultant gravito-inertial force that rotates backward and upward with respect to the pilot, causing him to perceive that he is suddenly upside down. Turbulent weather can produce additional inertial forces that contribute to the illusion. (Adapted from Martin and Jones (29).)

The G-excess illusion can also be considered a form of somatogravic illusion, because it involves an abnormal magnitude and/or direction of applied gravito-inertial force that results in false perception of body position, and the perceptual response can be determined at least qualitatively by a simple mechanical analysis (Fig. 33). Let us assume a subject is sitting upright in a $+1-G_z$ environment, and he tips his head forward 30 degrees. As a result of this change in head position, his otolithic membranes slide forward the appropriate amount for a 30-degree tilt relative to vertical--say, a distance of x μ m. Now suppose the same subject is sitting upright in a $+2-G_z$ environment, and again tips his head 30 degrees forward. This time his otolithic membranes slide forward more than x μ m because of the doubled gravito-inertial force acting on them. But the displacement of

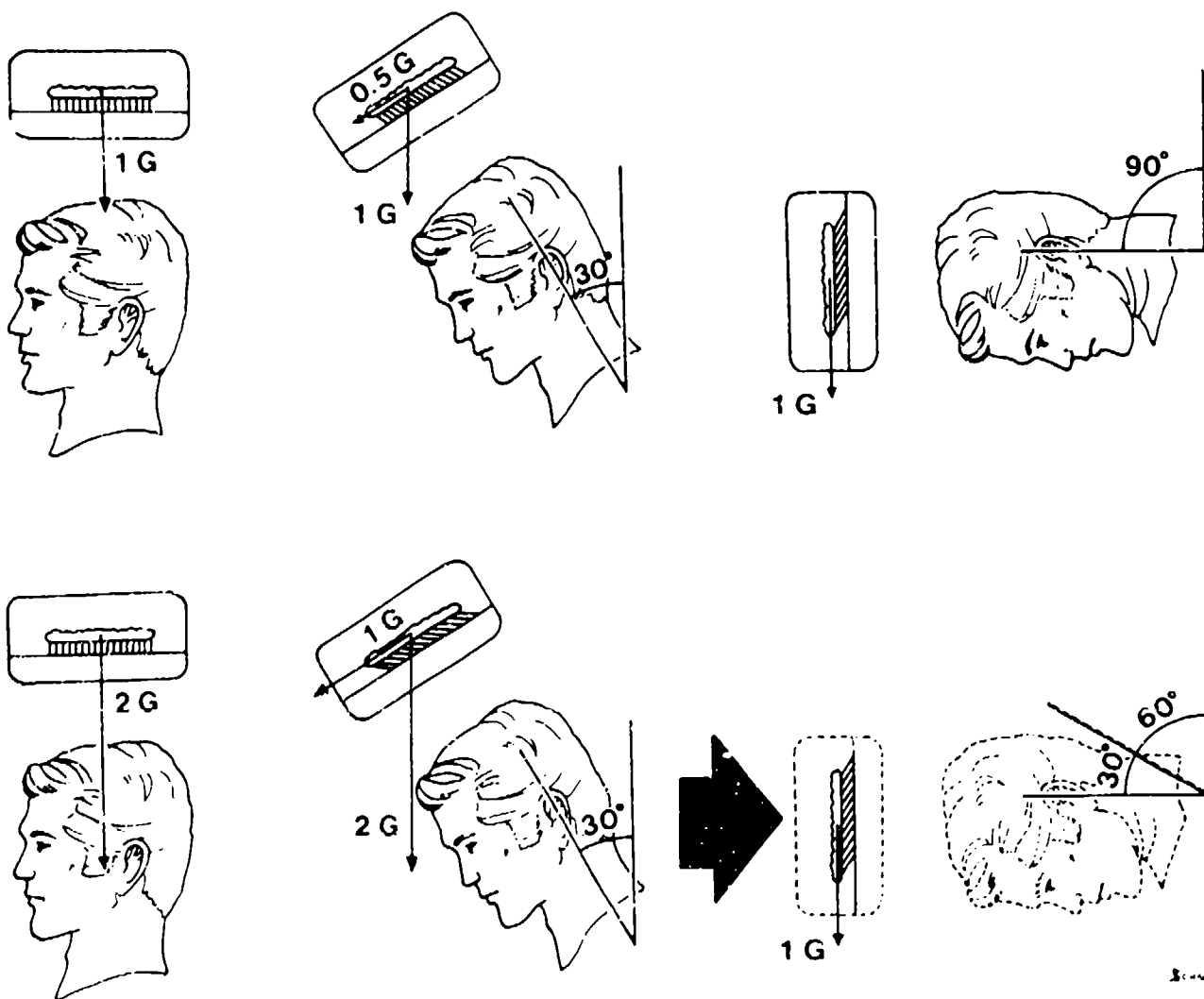


Figure 33. Mechanism of the G-excess illusion. Subject in 1-G environment (upper figures) experiences the result of a 0.5-G pull on his utricular otolithic membranes when he tilts his head 30 degrees off the vertical, and that of a 1-G pull when he tilts it a full 90 degrees. Subject in 2-G environment (lower figures) experiences the result of a 1-G pull when he tilts his head only 30 degrees. The illusory excess tilt perceived by the subject is attributed to external forces (lower right).

the otolithic membranes now corresponds not to a 30-degree forward tilt in the normal 1-G environment, but to a much greater one, theoretically as much as 90 degrees ($2 \sin 30 \text{ deg} = \sin 90 \text{ deg}$). The subject had initiated only a 30-degree head tilt, however, and expects to perceive no more than that. The unexpected additional perceived tilt is thus referred to the immediate environment; i.e., he perceives his vehicle, if he is in one, to have tilted by the amount equal to the difference between his actual and expected percepts of tilt. In a high-performance aircraft the G-excess illusion can occur as a result of the moderate amount of G force pulled in a turn--a penetration turn or procedure turn, for example. If the pilot has to look down and to the side to select a new radio frequency or to pick up a dropped pencil while in a turn, he should experience an uncommanded tilt in both the pitch and roll planes due to the G-excess illusion. As noted previously, the G-excess illusion may be responsible for the false sensation of pitch and/or roll generally attributed to the Coriolis illusion under such circumstances (31).

Another illusion of otolith-organ origin, but not classified as a somatogravic illusion because it involves a visual perceptual effect, is the oculogravic illusion. The oculogravic illusion can be thought of as a visual correlate of the somatogravic illusion, and occurs under the same stimulus conditions (32). A pilot who is subjected to the deceleration resulting from application of speed brakes, for example, experiences a nose-down pitch because of the somatogravic illusion. Simultaneously, he observes the instrument panel in front of him to move downward, confirming his sensation of tilting forward. The oculogravic illusion is thus the visually apparent movement of an object which is actually in a fixed position relative to the subject during changing magnitude and/or direction of the net gravito-inertial force. Like the oculogyral illusion, the oculogravic illusion probably results from the attempt to maintain visual fixation during a vestibulo-ocular reflex, elicited in this case by the change in magnitude or direction of the applied G vector rather than by angular acceleration.

The elevator illusion is a special type of oculogravic illusion that results from an increase or decrease in the magnitude of the $+G_z$ force acting on a subject. When one is accelerated upward, as in an elevator, the increase in $+G_z$ force elicits a vestibulo-ocular reflex of otolith-organ origin (the elevator reflex) that drives the eyes downward. Attempting to stabilize visually the objects in a fixed position relative to the observer causes those objects to appear to shift upward when the G force is increased. The opposite effect occurs when one is accelerated downward: the reduction in the magnitude of the net gravito-inertial force to less than $+1 G_z$ causes a reflex upward shift of the direction of gaze, and the immediate surroundings appear to shift downward. (The latter effect has also been called the oculogravic illusion because of its occurrence during transient weightlessness.) The importance of the elevator

illusion in aviation is not well documented. In one tragic mishap, however, it was probably experienced by the pilot of a military transport aircraft who became disoriented shortly after leveling off abruptly from a prolonged steady descent on a dark night over desert terrain. The transient increase in $+G_z$ force that occurred as the pilot leveled off at the landing pattern altitude most likely provoked the elevator illusion, and seeing his instrument panel rise, he compensated by pitching downward during the subsequent fatal turn to final approach. We can also assume that updrafts and downdrafts produce elevator illusions in pilots penetrating turbulent weather (Fig. 34).

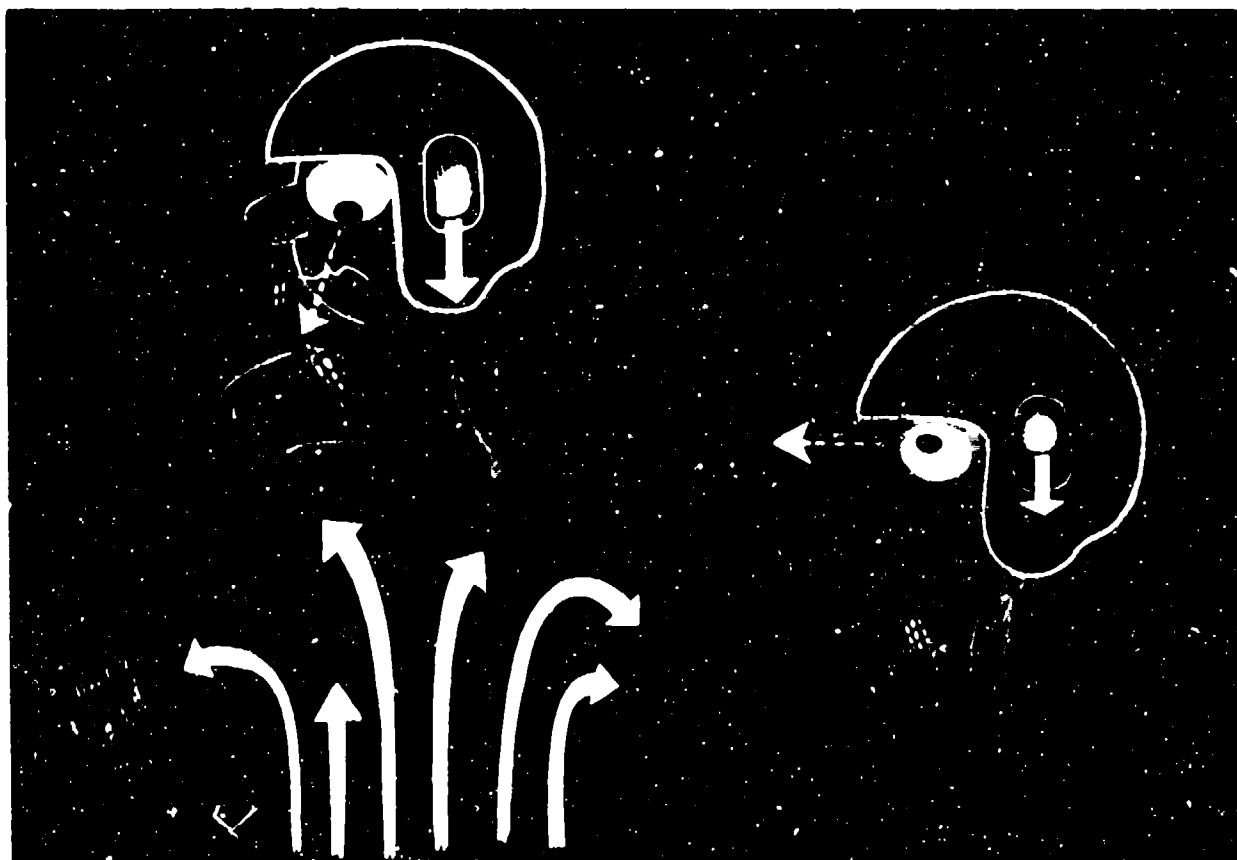


Figure 34. Elevator illusion resulting from an updraft. In this type of oculogravic illusion, the increase in $+G_z$ force elicits a vestibulo-ocular reflex of otolith-organ origin which, when visual fixation is attempted, results in a falsely perceived upward motion of the object fixated--the instrument panel in the example shown.

By far the most common vestibular illusion in flight is the leans. Virtually every instrument-rated pilot has had it, or will get it, in one form or another at some time in his flying career. It consists of a false percept of angular displacement about the roll axis, i.e., is an illusion of bank, and is frequently associated with an attempt by the pilot to compensate for the illusion by leaning in the direction of the falsely perceived vertical (Fig. 35). The usual explanations of the leans invoke the known deficiencies of both otolith-organ and semicircular-duct sensory mechanisms. As indicated previously, the otolith organs are not reliable sources of information about the direction of the true vertical because they respond to the resultant gravito-inertial force, not to gravity alone. Furthermore, other sensory inputs can sometimes override otolith-organ cues and result in false perception of the vertical, even when the gravito-inertial force experienced is truly vertical. The semicircular ducts can provide such false inputs in flight by responding accurately to some roll stimuli but not responding to others because they are below threshold. If, for example, a pilot is subjected to an angular acceleration in roll so that the product of the acceleration and its time of application does not reach some threshold value--say, 3 degrees/s--then he does not perceive the roll. Let us suppose this pilot, who is trying to fly straight and level, is subjected to an unrecognized and uncorrected 2-degree/s roll for 10 s: a 20-degree bank results. If the pilot suddenly notices the unwanted bank and corrects it by rolling the aircraft back upright with a suprathreshold roll rate--say, 15 degrees/s--he experiences only half of the actual roll motion that took place, the half resulting from the correcting roll. As he started perceptually from a wings-level position, he is left with the illusion of having rolled into a 20-degree bank in the direction of the correcting roll, even though he is again wings-level. At this point he has the leans; and although he may be able to fly the aircraft properly by the very deliberate and difficult process of forcing the attitude indicator to read correctly, his illusion can last for many minutes, seriously degrading his flying efficiency during that time.

Interestingly, pilots frequently get the leans after prolonged turning maneuvers, and not because of alternating subthreshold and suprathreshold angular motion stimuli. In a holding pattern, for example, the pilot rolls into a 3-degree/s standard-rate turn, holds the turn for 1 min, rolls out and flies straight and level for 1 min, turns again for 1 min, and so on until traffic conditions permit him to proceed toward his destination. During the turning segments the pilot initially feels the roll into the turn and accurately perceives the banked attitude. But as the turn continues, his percept of being in a banked turn dissipates and is replaced by a feeling of flying straight and level, both because the sensation of turning is lost when the endolymph comes up to speed in the semicircular ducts (somatogyral illusion) and because the net G force being directed toward the floor of the aircraft provides a false cue

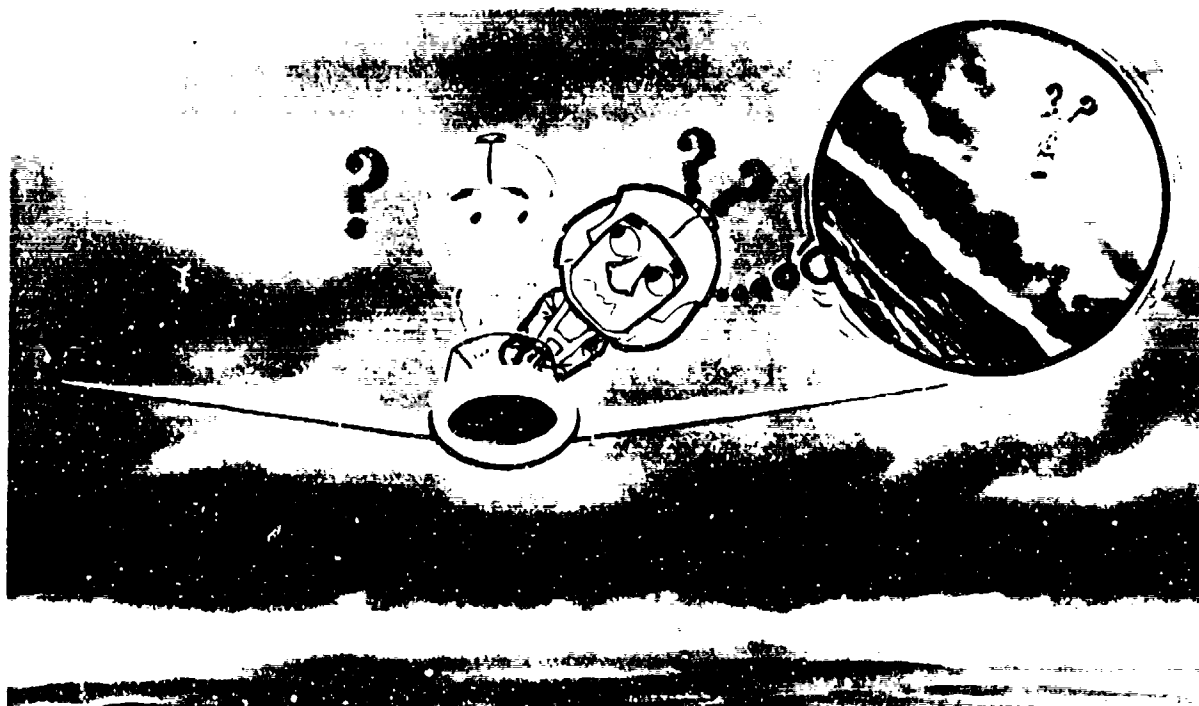


Figure 35. The leans, the most common of all vestibular illusions in flight. Falsely perceiving himself to be in a right bank, but flying the aircraft straight and level by means of the flight instruments, this pilot is leaning to the left in an attempt to assume an upright posture compatible with his illusion of bank.

of verticality (somatogravic illusion). When the pilot then rolls out of the turn, he feels he has rolled into a banked turn in the opposite direction. With experience, a pilot learns to suppress this false sensation quickly by paying strict attention to the attitude indicator. Sometimes, however, the pilot finds he cannot dispel the illusion of banking--usually when he is particularly busy, unfortunately. The leans can also be caused by misleading peripheral visual orientation cues, as mentioned in the discussion of the visual illusions. Roll angularvection is particularly effective in this regard, at least in the laboratory. One thing about the leans is obvious: there is no single explanation for it. The deficiencies of several orientation-sensing systems in some cases reinforce each other to create an illusion; in other cases the inaccurate information from one sensory modality for some reason is selected over the accurate information from others to create the illusion. Stories have surfaced of pilots suddenly experiencing the leans for no apparent reason at all, or even of experiencing it voluntarily by imagining the earth to be in a different direction from the aircraft. The point is that one must not think that the leans, or any other illusion for that matter, occurs as a totally predictable response to a physical stimulus: there is much more to perception than stimulation of the end-organs.

Disorientation in Flight

Definitions. We have already defined an orientational illusion to be a false percept of position, attitude, or motion, relative to the plane of the earth's surface. Spatial disorientation and the equivalent term, pilot vertigo, are usually taken to mean the experiencing of an orientational illusion in flight. There is a major qualitative difference, however, between simply experiencing an orientational illusion and having to control an aircraft under conditions of misperceived or conflicting orientation cues. Furthermore, this difference becomes very important in the analysis of mechanisms involved in aircraft mishaps due to orientational illusions, and in the development of training aids for educating pilots about the potential for loss of aircraft control while under the influence of orientational illusions. For those reasons, we find it necessary to restrict the use of the term spatial disorientation to the condition wherein one not only has an orientational illusion but also needs to have correct perception of orientation for controlling his position, attitude, or motion. When one has an orientational illusion but has no need for correct information about his orientation, we say he has spatial unorientation. This distinction is exemplified by the contrast between the experience of a pilot, who must fly his vehicle on a desired path through space by responding to available orientation cues (and to whom such cues are, therefore, highly relevant), and the experience of an airborne communications monitor, who can perform his duty without regard to his spatial orientation (and to whom orientation cues--whether true or false--are essentially irrelevant). Obviously, it is spatial disorientation, not spatial unorientation, that causes aircraft mishaps and warrants investigative and educational efforts to prevent it.

Types. It is also useful to make the distinction between unrecognized (also called Type I) and recognized (Type II) spatial disorientation. As the term implies, unrecognized spatial disorientation refers to the situation in which a pilot, oblivious to the fact that he is disoriented, controls his vehicle completely in accord with and in response to his false orientational percept. In recognized spatial disorientation the pilot realizes something is wrong with his ability to fly the vehicle, but he may or may not actually realize that the source of his problem is spatial disorientation. Even further out in the spectrum of types of disorientation is that in which the pilot not only recognizes that he cannot control his vehicle effectively because of spatial disorientation, but he also cannot obtain correct orientation information because the violence of the motion imposed is blurring his vision with counterproductive vestibulo-ocular reflexes (nystagmus). For want of an adequately descriptive simple term we shall call this type vestibulo-ocular disorganization, or Type III spatial disorientation.

Examples. The last of four F-15 Eagle fighter aircraft took off on a daytime sortie in weather, intending to follow the

other three in a radar in-trail departure. Because of a navigational error committed by the pilot shortly after takeoff, he was unable to acquire the other aircraft on his radar. Frustrated, he elected to intercept the other aircraft where he knew they would be in the arc of the standard instrument departure; so he made a bee-line for that point, presumably scanning his radar diligently for the blips he knew should be appearing at any time. Meanwhile, after ascending to 1200 m (4000 ft) above ground level, he entered a descent of approximately 12 m/s (2400 ft/min) as a result of an unrecognized 3-degrees-nose-low attitude. After receiving requested position information from another member of the flight, the mishap pilot suddenly realized he was in danger of colliding with the others, or he suddenly acquired them on radar: he then made a steeply banked turn, either to avoid a perceived threat of collision or to join up with the rest of the flight. Unfortunately, he had by this time descended far below the other aircraft and was going too fast to avoid the ground, which became visible under the overcast just before the aircraft crashed. This mishap resulted from an episode of unrecognized, or Type I, disorientation. The specific illusion responsible appears to have been the somatogravic illusion, created by the forward acceleration of this high-performance aircraft during takeoff and climb-out. The pilot's preoccupation with the radar task compromised his instrument scan to the point where the false vestibular cues were able to penetrate his orientational information processing. Having unknowingly accepted an inaccurate orientational percept, he controlled the aircraft accordingly until it was too late to recover.

Examples of recognized, or Type II, spatial disorientation are easier to obtain than are examples of Type I, as most experienced pilots have anecdotes to tell about how they "got vertigo" and fought it off. Some pilots were not so fortunate, however. One F-15 Eagle pilot, after climbing his aircraft in formation with another F-15 at night, began to experience difficulty maintaining spatial orientation and aircraft control upon leveling off in clouds at 8200 m (27,000 ft). "Talk about practice bleeding," he commented to the lead pilot. Having decided to go to another area because of the weather, the two pilots began a descending right turn. At this point the pilot on the wing told the lead pilot, "I'm flying upside down." Shortly afterward the wingman considered separating from the formation, saying, "I'm going lost wingman;" then, "No, I've got you;" and finally, "No, I'm going lost wingman." The mishap aircraft then descended in wide spiral, crashing into the desert less than a minute later, even though the lead pilot advised the wingman several times during the descent to level out. In this mishap the pilot probably suffered an inversion illusion upon leveling off in the weather, and entered a graveyard spiral after leaving the formation. Although he knew he was disoriented, or at least recognized the possibility, he still was unable to control the aircraft effectively. That a pilot can realize he is disoriented, see accurate orientation information displayed on the attitude indicator, and still fly into the

ground, always strains the credulity of nonaviators. Pilots who have had spatial disorientation, who have experienced fighting oneself for control of an aircraft, are less skeptical.

The pilot of an F-15 Eagle, engaged in vigorous air combat tactics training with two other F-15s on a clear day, initiated a hard left turn at 5200 m (17,000 ft) above ground level. For reasons that have not been established with certainty, his aircraft began to roll to the left at a rate estimated at 150 to 180 degrees/s. He transmitted, "Out-of-control autoroll," as he descended through 4600 m (15,000 ft). The pilot made at least one successful attempt to stop the roll, as evidenced by the momentary cessation of the roll at 2400 m (8,000 ft); then the aircraft began to roll again to the left. Forty seconds elapsed between when the rolling began and when the pilot ejected--but too late. Regardless of whether the rolling was caused by a mechanical malfunction or was induced by the pilot himself, the certain result of this extreme motion was vestibulo-ocular disorganization, which not only prevented the pilot from reading his instruments but also kept him from orienting with the natural horizon. Thus, Type III disorientation probably prevented him from taking appropriate corrective action to stop the roll and keep it stopped; if not that, it certainly compromised his ability to assess accurately the level to which his situation had deteriorated.

Statistics. Despite continuing efforts to educate pilots about spatial disorientation and the real hazard it represents, the fraction of aircraft mishaps caused by or contributed to by spatial disorientation remained fairly constant over the three decades between 1950 and 1980. A number of statistical studies of spatial disorientation mishaps bear this out for the United States Air Force. In 1956 Nuttall and Sanford reported that, in one major air command during the period 1954-1956, spatial disorientation was responsible for 4% of all major aircraft mishaps and 14% of all fatal aircraft mishaps (33). Moser in 1969 reported a study of aircraft mishaps in another major air command during the four-year period, 1964-1967: he found that spatial disorientation was a significant factor in 9% of major mishaps and 26% of fatal mishaps (34). In 1971 Barnum and Bonner reviewed the Air Force mishap data from 1958 through 1968, and found that in 281 or 6% of the 4,679 major mishaps, spatial disorientation was a causative factor; fatalities occurred in 211 of those 281, accounting for 15% of the 1,462 fatal mishaps (35). A comment by Barnum and Bonner summarizes some interesting data about the "average pilot" involved in a spatial disorientation mishap: "He will be around 30 years of age, have 10 years in the cockpit, and have 1,500 hours of first pilot/instructor-pilot time. He will be a fighter pilot and will have flown approximately 25 times in the three months prior to his accident." Barnum next analyzed the mishap data for the three-year period, 1969-1971, and concluded that spatial disorientation mishaps again accounted for 6% of major mishaps, but only for 10% of fatal mishaps during this period (36). In a

1973 study, Kellogg found the relative incidence of Air Force spatial disorientation mishaps in the years 1968 through 1972 to range from 4.8 to 6.2%, and confirmed the high proportion of fatalities in mishaps resulting from spatial disorientation (37). In 1980 Gillingham and Page (unpublished data) reviewed the Air Force aircraft mishaps of 1979 and determined that at least 9 of the 94 major mishaps (9.6%) and 9 of the 49 fatal mishaps (18.4%) occurring that year would not have occurred had the pilots not been spatially disoriented at some time during the mishap sequence. The cost of the Air Force aircraft destroyed each year in disorientation mishaps has been until recently on the order of \$20 million per year. In 1979 it was \$40 million; and the figure continues to rise, mainly as a result of the rapidly rising cost of new military aircraft. Statistics on the incidence of disorientation-related aircraft mishaps in the United States Army and Navy (7.11% and 6.75% of total mishaps, respectively) (38,39) are remarkably similar to those of the Air Force, even though the flying missions of the several military services are somewhat different.

Although statistics indicating the relative frequency of spatial disorientation mishaps in air-carrier operations are not readily available, it would be a serious mistake to conclude that there have been no air-carrier mishaps caused by spatial disorientation. Fourteen such mishaps occurring between 1950 and 1969 were reportedly due to somatogravic and visual illusions resulting in the so-called "dark-night-takeoff accident" (28). In addition, 26 commercial airliners were involved in jet-upset incidents or accidents during the same period (30). Spatial disorientation is also a problem in general (non-military, non-air-carrier) aviation. Kirkham et al. reported in 1978 that, although spatial disorientation is a cause or factor in only 2.5% of all general aviation aircraft accidents in the United States, it is the third most common cause of fatal general aviation accidents: 627 of the 4,012 fatal mishaps (15.6%) occurring in the years 1970 through 1975 involved spatial disorientation as a cause or factor (40). Furthermore, the contribution of spatial disorientation to the second most common cause of fatal general aviation accidents--continued VFR flight into adverse weather--is undoubtedly highly significant. Notably, 90% of general aviation mishaps in which disorientation is a cause or factor are fatal.

Dynamics of Spatial Orientation and Disorientation. It is naive to assume that a certain pattern of physical stimuli always elicits a particular veridical or illusory perceptual response. Certainly, when a pilot has a wide, clear view of the horizon, ambient vision supplies virtually all of his orientation information; and potentially misleading linear or angular acceleratory motion cues do not result in spatial disorientation (unless, of course, they are so violent as to cause vestibulo-ocular disorganization). When a pilot's vision is compromised by weather, the same acceleratory motion cues can cause him to develop spatial disorientation, but he usually avoids it by

referring to his aircraft instruments for orientation information. If the pilot is unskilled at interpreting the instruments, or if the instruments fail, those misleading motion cues inevitably cause disorientation. Such is the character of visual dominance, the phenomenon wherein one incorporates visual orientation information into his percept of spatial orientation, to the exclusion of vestibular and nonvestibular proprioceptive, tactile, and other sensory cues. Visual dominance falls into two categories: the congenital type, in which ambient vision provides dominant orientation cues through natural neural connections and functions; and the acquired type, in which orientation cues are gleaned through focal vision and are integrated as a result of training and experience into an orientational percept. The functioning of the proficient instrument pilot illustrates acquired visual dominance: he has learned to decode with foveal vision the information on the attitude indicator and other flight instruments and to reconstruct that information into a concept of where he is, what he is doing, and where he is going; and he refers to that concept when controlling his aircraft. This complex skill must be developed through training and maintained through practice; and it is the fragility of this acquired visual dominance that makes spatial disorientation such a hazard.

The term vestibular suppression is often used to denote the active process of visually overriding undesirable vestibular sensations or vestibulo-ocular reflexes. An example of this aspect of visual dominance is seen in well-trained figure skaters who, with much practice, learn to abolish the post-rotatory dizziness and nystagmus that normally result from the very high angular decelerations associated with suddenly stopping rapid spins on the ice (41). But even these individuals, when deprived of vision by eye closure or darkness, have the very dizziness and nystagmus we would expect to result from the acceleratory stimuli generated (42). In flight, the ability to suppress unwanted vestibular sensations and reflexes is developed with repeated exposure to the linear and angular accelerations of flight. As is the case with the figure skaters, however, the pilot's ability to prevent vestibular sensations and vestibulo-ocular reflexes is compromised when he is deprived of visual orientation cues--when he must look away from his attitude indicator to manipulate a radio frequency-selector knob, for instance.

At this point, we introduce the concept of vestibular opportunism. By this is meant the propensity of the vestibular system to fill an orientation-information void swiftly and surely with vestibular information. When a pilot flying in instrument weather looks away from his artificial horizon for a mere few seconds, this is usually long enough for erroneous vestibular information to break through the pilot's defenses and become incorporated into his orientational percept. In fact, conflicts between focal visual and vestibular sources of orientation information tend to resolve themselves very quickly in

favor of the vestibular information, without providing the pilot an opportunity to evaluate the information. It would seem that any orientation information reaching the vestibular nuclei--whether vestibular, other proprioceptive, or ambient visual--should have an advantage in competing with focal visual cues for expression as the pilot's sole orientational percept, because the vestibular nuclei are primary terminals in the pathways for reflex orientational responses, and are the initial level of integration for any eventual conscious concomitant of perception of spatial orientation. In other words, although acquired visual dominance can be maintained by diligent attention to artificial orientation cues, the challenge to this dominance presented by the processing of natural orientation cues through primitive neural channels is very potent and ever present.

The lack of adequate orientation cues, and conflicts between competing sensory modalities, are only a part of the whole picture of a disorientation mishap. Why so many disoriented pilots, even those who know they are disoriented, are unable to recover their aircraft has mystified aircraft accident investigators for decades. There are two possible explanations for this phenomenon. The first suggests that the psychologic stress of disorientation results in a disintegration of higher-order learned behavior, including flying skills. The second describes a complex psychomotor effect of disorientation that causes the pilot to feel the aircraft itself is misbehaving.

The disintegration of flying skill perhaps begins with the pilot's realization that his spatial orientation and control over the motion of his aircraft have been compromised. Under such circumstances, he pays more heed to whatever orientation information is naturally available, monitoring it more and more vigorously. Whether the brain stem reticular activating system or the vestibular efferent system, or both, are responsible for the resulting heightened arousal and enhanced vestibular information flow can only be surmised; but the net effect is that more erroneous vestibular information is processed and incorporated into the pilot's orientational percept. This, of course, only makes matters worse. A positive-feedback situation is thus encountered, and the vicious circle can now be broken only with a precisely directed, and very determined, effort by the pilot. Unfortunately, complex cognitive and motor skills tend to be degraded under conditions of psychologic stress such as occurs during Type II or Type III spatial disorientation. First, there is a coning of attention. Pilots who have survived severe disorientation have reported they were concentrating on one particular flight instrument instead of scanning and interpreting the whole group of them in the usual manner. Pilots have also reported they were unaware of radio transmissions to them while they were trying to recover from disorientation. Second, there is the tendency to revert to more primitive behavior, even reflex action, under conditions of severe psychologic stress. The highly developed, relatively newly acquired skill of instrument flying can give way to primal protective

responses during disorientation stress, making appropriate recovery action unlikely. Third, it is often suggested that disoriented pilots become totally immobilized--frozen to the aircraft controls by fear or panic--as the disintegration process reaches its final state.

The giant hand phenomenon, described by Malcolm and Money (30), undoubtedly explains why many pilots have been rendered hopelessly confused and ineffectual by spatial disorientation, even though they knew they were disoriented and should have been able to avoid losing control of their aircraft. The pilot suffering from this effect of disorientation perceives falsely that his aircraft is not responding properly to his control inputs, because every time he tries to bring the aircraft to the desired attitude, it seems actively to resist his effort and fly back to another, more stable, attitude. A pilot experiencing disorientation about the roll axis (e.g., the leans or graveyard spiral) may feel a force--like a giant hand--trying to push one wing down and hold it there, while the pilot with pitch-axis disorientation (e.g., the classic somatogravic illusion) may feel the airplane subjected to a similar force trying to hold the nose down. Pilots who are unaware of the existence of this phenomenon and experience it for the first time can be very surprised and confused by it, and may not be able to discern the exact nature of their problem. A pilot's radio transmission that the aircraft controls are malfunctioning should not, therefore, be taken as conclusive evidence that a control malfunction caused a mishap: spatial disorientation could have been the real cause.

What mechanism could possibly explain the giant hand? To try to understand this phenomenon, we must first recognize that our perception of orientation results not only in the conscious awareness of our position and motion but also in a preconscious percept needed for proper performance of voluntary motor activity and reflex actions. A conscious orientational percept can be considered rational, in that we can subject it to intellectual scrutiny, weigh the evidence for its veracity, conclude that it is inaccurate, and to some extent modify the percept to fit facts obtained from other than the primary orientation senses. In contrast, a preconscious orientational percept must be considered irrational, in that it consists only of an integration of data relayed to the brain stem and cerebellum by the primary orientation senses, and is not amenable to modification by reason. So what happens when a pilot knows he has become disoriented and tries to control his aircraft by reference to a conscious, rational percept of orientation which is at variance with his preconscious, irrational one? Because only the data comprising one's preconscious orientational percept are available for the performance of primitive orientational reflexes (e.g., vestibulo-ocular and postural reflexes), higher-order reflexes (e.g., aversive responses), and skilled voluntary motor activity (e.g., walking, running, bicycling, driving, flying), we should expect the actual outcome of these types of actions to deviate

from the rationally intended outcome whenever the orientational data upon which they depend are different from the rationally perceived orientation. The disoriented pilot who consciously commands a roll to recover aircraft control, while the informational substrate in reference to which his body functions indicates that such a move is counterproductive or even dangerous, may experience a great deal of difficulty in executing the command. Or he may discover that the roll, once accomplished, must be reaccomplished repeatedly, as his body responds automatically to the preconsciously perceived orientational threat resulting from his conscious efforts and actions to regain control. Thus, the preconscious orientational percept influences Sherrington's "final common pathway" for both reflex and voluntary motor activity; and the manifestation of this influence on the act of flying during an episode of spatial disorientation is the giant hand phenomenon. To prevail in this conflict between his will and his skill, the pilot must decouple his voluntary acts from his previously learned flying behavior, by accomplishing those motions which produce directly the desired readings of the flight instruments, rather than by flying the airplane to an attitude corresponding to the desired readings of the flight instruments.

The salient features of the dynamics of spatial orientation and disorientation are diagrammed in Figure 36; the concepts of visual dominance, vestibular suppression, vestibular opportunism, disintegration of flying skill, conscious and preconscious orientational percepts, and the giant hand phenomenon are presented therein as they relate to the overall scheme of orientation-information processing.

Conditions Conducive to Disorientation. From a knowledge of the physical bases of the various illusions of flight one can readily infer many of the specific environmental factors conducive to spatial disorientation. Certain visual phenomena produce characteristic visual illusions, such as false horizons, linear and angular vection, and autokinesis. Prolonged turning at a constant rate, as in a holding pattern or procedure turn, can precipitate somatogyral illusions or the leans; and Coriolis illusions can conceivably occur with head movements under these conditions. Relatively sustained linear accelerations, such as those that occur on takeoff, can produce somatogravic illusions; and head movements during G-pulling turns can elicit G-excess illusions.

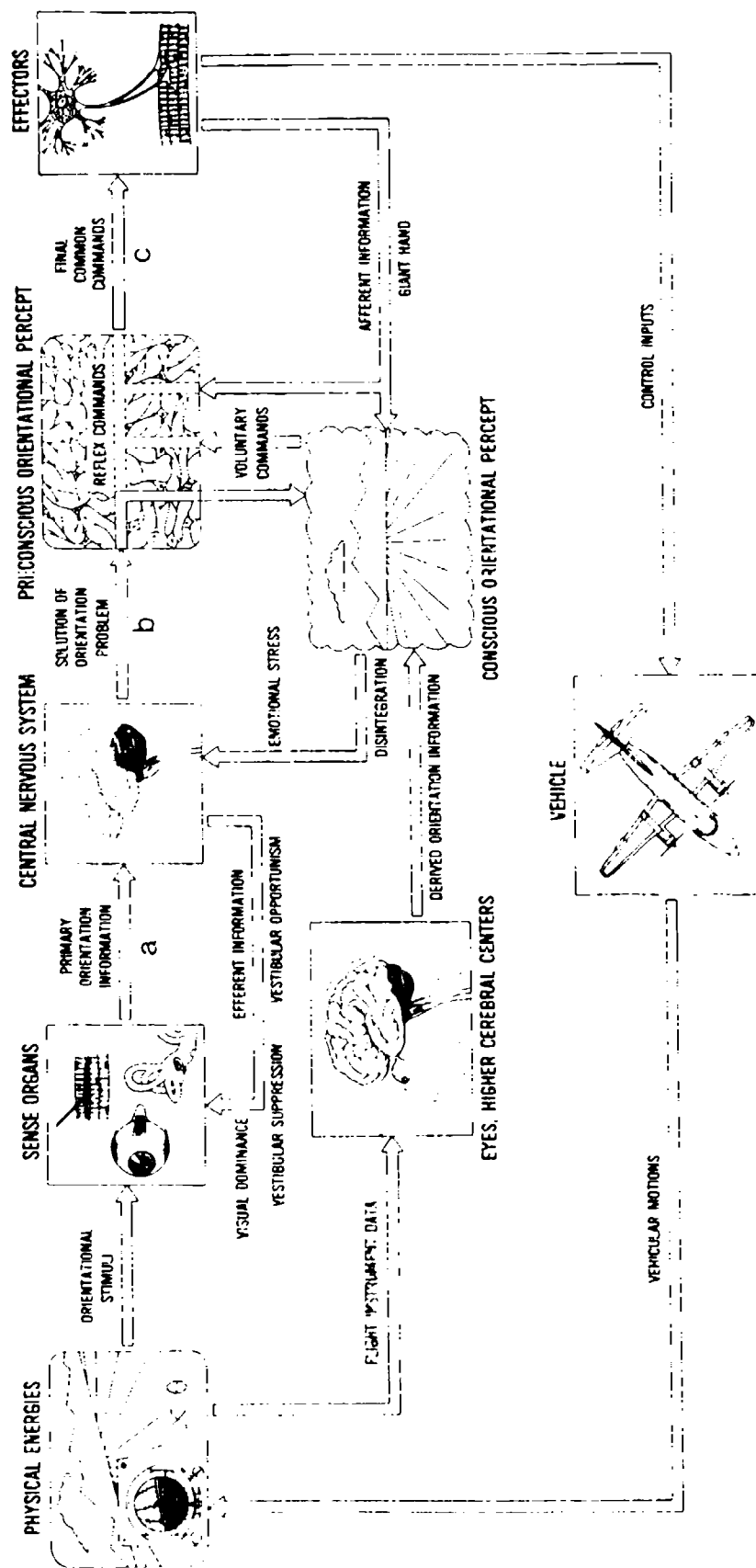
What are the regimes of flight and activities of the pilot that seem most likely to allow these potential illusions to manifest themselves? Certainly, instrument weather and night flying are primary factors. But especially likely to produce disorientation is the practice of switching back and forth between the instrument flying mode and the visual or contact flying mode; a pilot is far less likely to become disoriented if he gets on the instruments as soon as out-of-cockpit vision is compromised and stays on the instruments until continuous

contact flying is again assured. In fact, any event or practice requiring the pilot to break his instrument cross-check is conducive to disorientation. In this regard, avionics control switches and displays in some aircraft are located where the pilot must interrupt his instrument cross-check for more than a few seconds to interact with them, and are thus known (not so affectionately) as "vertigo traps." Some of these vertigo traps require substantial movements of the pilot's head during the time his cross-check is interrupted, thereby providing both a reason and an opportunity for spatial disorientation to strike.

Formation flying in weather is probably the most likely of all situations to produce disorientation; indeed, some experienced pilots get disoriented every time they fly wing or trail in weather. The fact that a pilot has little if any opportunity to scan his flight instruments while flying formation on his lead aircraft in weather means he is essentially isolated from any source of accurate orientation information, and misleading vestibular and ambient visual cues arrive unchallenged into his sensorium.

Of utmost importance to a pilot in preventing spatial disorientation is competency and currency in instrument flying. A non-instrument-rated pilot who penetrates instrument weather is virtually assured of developing spatial disorientation within a matter of seconds, just as the most competent instrument pilot would develop it if he found himself flying in weather without functioning flight instruments. Regarding instrument flying skill, one must "use it or lose it," as they say. For that reason pilots whose primary flying activity involves missions or environments in which instrument weather is rarely encountered (e.g., air combat training in the United States Southwest) must aggressively seek opportunities to practice instrument flying so as to maintain their proficiency at it. Otherwise, they could discover that their instrument flying skill has deteriorated to a dangerously low level during a rare occasion when that skill is really needed.

Finally, conditions affecting the pilot's physical or mental health must be considered capable of rendering the pilot more susceptible to spatial disorientation. The unhealthy effect of alcohol ingestion on neural information processing is one obvious example; but the less well-known ability of alcohol to produce vestibular nystagmus (positional alcohol nystagmus--PAN) for many hours after its more overt effects have disappeared is probably of equal significance. Other drugs, such as barbiturates, amphetamines, and even the quinine in tonic water, are suspected of possibly having contributed to aircraft mishaps resulting from spatial disorientation. Likewise, physical and mental fatigue, as well as acute or chronic emotional stress, can rob the pilot of his ability to concentrate on his instrument cross-check, and can therefore have deleterious effects on his resistance to spatial disorientation.



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Figure 36. Flow of orientation information in flight. The primary information-flow loop involves: stimulation of the visual, vestibular, and other orientation senses by visual scenes and linear and angular accelerations; processing of this primary orientation information by brain stem, cerebellum, and lower cerebral centers; incorporating the solution into a data base for reflexive and skilled voluntary motor activity (preconscious orientational percept); and effecting control inputs, which produce aircraft motions that result in orientational stimuli. A secondary path of information flow involves the processing of largely numerical data from flight instruments into derived orientation information by higher cerebral centers. Subloop a provides for feedback between various components of the nervous system, and includes efferent system influences on the sensory end-organs themselves. The phenomena of visual dominance, vestibular suppression, and vestibular opportunism occur in conjunction with the functioning of this loop. Subloop b generates conscious perception of orientation, both from the body's naturally obtained solution of the orientation problem and from orientation information derived from flight instrument data. Voluntary control commands arise in response to conscious orientational percepts; and the psychic stress resulting from conflicting orientation information or from apparently aberrantly responding effectors can influence the manner in which orientation information is processed, leading ultimately to disintegration of flying skill. Subloop c incorporates feedback from muscles, tendons, and joints involved in making control inputs, and provides a basis for the giant hand phenomenon.

Prevention of Disorientation Mishaps

Spatial disorientation can be attacked in several ways. Theoretically, each link in the physiologic chain of events leading to a disorientation mishap can be broken by a specific countermeasure (Fig. 37). Spatial disorientation can many times be prevented by modifying flying procedures so as to avoid those visual or vestibular stimuli that tend to create illusions in flight. By improving the capacity of flight instruments to translate aircraft position and motion information into readily assimilable orientation cues, we can help the pilot avoid

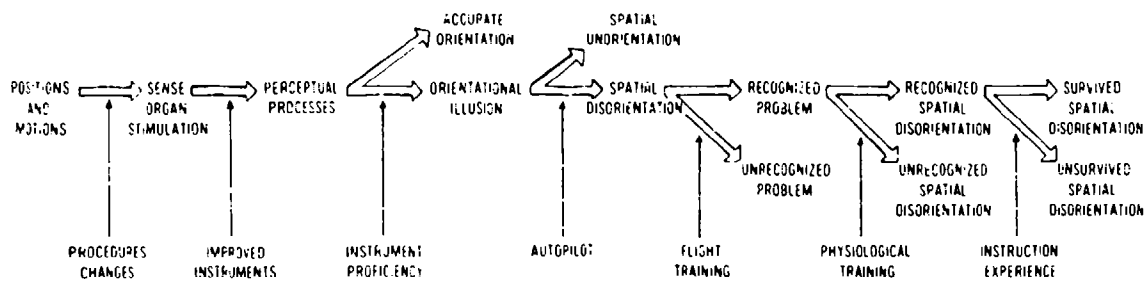


Figure 37. The chain of events leading to a spatial disorientation mishap, and where the chain can be attacked and broken. From left: Flight procedures can be altered to generate less confusing sensory inputs. Improved instrument presentations can aid assimilation of orientation cues. Proficiency in instrument flying helps assure accurate orientational percepts. In the event the pilot suffers an orientational illusion, having the aircraft under autopilot control avoids disorientation by substituting unorientation. Proper flight training allows the disoriented pilot to recognize he is having a problem controlling his craft. Once he knows he is having a problem, his physiological training helps him realize his problem is spatial disorientation. With appropriate instruction and/or firsthand experience, the pilot with recognized spatial disorientation can apply the correct control forces to recover the aircraft and survive the disorientation incident.

disorientation. Through repeated exposure to the environment of instrument flight, the pilot becomes proficient in instrument flying; this involves developing perceptual processes that result in accurate orientational percepts rather than orientational illusions. If a pilot who is experiencing an illusion can relinquish control of his aircraft to an autopilot, he can convert his situation from one of hazardous spatial disorientation to one of irrelevant spatial unorientation, and reclaim control once the orientational illusion has subsided. Use of the autopilot, not only to help the pilot recover from disorientation, but also to help prevent it in the first place, is a technique that has considerable potential for saving lives, particularly in general aviation. Given that a pilot has developed spatial disorientation, if he can be made to recognize that he is disoriented, he is halfway along the road to recovery. To recognize disorientation is not necessarily easy, however. First, the pilot must recognize that he is having a problem holding his altitude or heading; this he cannot do if he is concentrating on something other than the flight instruments--on the radar scope, for instance. Only through proper flight

training can the discipline of continuously performing the instrument cross-check be instilled. Second, the pilot must recognize that his difficulty in controlling the aircraft is a result of spatial disorientation. This ability is promoted through physiological training. We said that the pilot who suspects he is disoriented is halfway down the road to recovery: why not most of the way? Because a pilot's ability to cope with the effects of disorientation on his control inputs to the aircraft comes through effective flight instruction, proper physiological training, and experience in controlling his vehicle in an environment of conflicting orientation cues--his simply being aware that he is disoriented by no means ensures his survival.

Education and Training. Physiological training is the main weapon against spatial disorientation at the disposal of the flight surgeon and aerospace physiologist. This training ideally should consist of both didactic material and demonstrations. There is no paucity of didactic material on the subject of disorientation: at least eight films, five video-cassette tapes, three slide sets, two handbooks, and numerous chapters in books and manuals have been prepared for the purpose of informing the pilot about the mechanisms and hazards of spatial disorientation. Although the efforts to generate information on spatial disorientation are commendable, there has been a tendency for the didactic material thus far produced to dwell too much on mechanisms and effects of disorientation without giving much practical advice on how to deal with it. Money and Malcolm (43) noted that none of the available films on spatial disorientation gives sufficient emphasis to what the pilot should do when he suspects disorientation. While several of the films recommend that the pilot believe his instruments, this message is too subdued and, by itself, is inadequate. Money and Malcolm argue that under some circumstances (e.g., panic) a pilot may in fact believe the instruments but continue to fly the aircraft according to his false orientational percept. If a pilot is told in addition, "Make the instruments read right, regardless of your sensations," he has simple, definite instructions on how to bring the aircraft under control when disorientation strikes. We strongly advise, therefore, that every presentation to pilots on the subject of spatial disorientation emphasize the need to make the instruments read right, as well as to believe them, when responding to disorientation stress.

The traditional demonstration accompanying lectures to pilots on spatial disorientation is a ride on a Barany chair or other smoothly rotating device. The subject, sitting in the device with his eyes closed, is accelerated to a constant angular velocity and asked to signal with his thumbs his perceived direction of turning. After a number of seconds (usually from 10 to 20, at constant angular velocity, the subject loses the sensation of rotation and signals this fact to the observers. Then the instructor suddenly stops the rotation,

whereupon the subject immediately indicates that he feels he is turning in the direction opposite his original direction of rotation. The subject is usually asked to open his eyes during this part of the demonstration, and is amazed to see that he is actually not turning, despite the strong vestibular sensation of rotation. After the described demonstration of somatogyral illusions, the subject is again rotated at a constant velocity with his eyes closed, this time with head down (facing the floor). When the subject indicates his sensation of turning has ceased, he is asked to raise his head abruptly so as to face the wall. The Coriolis illusion resulting from this maneuver is one of a very definite roll to one side: the startled subject may exhibit a protective postural reflex, and may open his eyes to help him visually orient during his falsely perceived upset. The message delivered with these demonstrations is not that such illusions will be experienced in flight in the same manner, but that the vestibular sense can be fooled--i.e., is unreliable--and that only the flight instruments provide accurate orientation information.

Over the years at least a dozen different devices have been developed to augment or supplant the Barany chair for demonstrating various vestibular and visual illusions and the effects of disorientation in flight. These devices, collectively known as antivertigo trainers, fall into two basic categories: orientational illusion demonstrators and spatial disorientation demonstrators. The great majority are illusion demonstrators, in which the subject rides passively and experiences one or more of the following: somatogyral, oculogyral, somatogravic, oculogravic, Coriolis, G-excess,vection, and autokinetic illusions. In an illusion demonstrator, the subject typically is asked to record or remember the magnitude and direction of the orientational illusion, and then is told or otherwise allowed to experience his true orientation. A few antivertigo trainers are actually spatial disorientation demonstrators, which allow the subject to experience the difficulty in controlling the attitude and motion of the trainer while being subjected to somatogravic, somatogyral, and/or Coriolis illusions. Figure 38 shows two antivertigo trainers presently in use in the United States Air Force. One must be aware that the name given to any particular antivertigo trainer does not necessarily describe its function: The USAFSAM Spatial Disorientation Demonstrator, for example, was actually an orientational illusion demonstrator.

Although the maximum use of antivertigo trainers in physiological training of pilots is to be encouraged, it is important to recognize the great potential for misuse of such devices by personnel not thoroughly trained in their theory and function. Several antivertigo trainers have aircraft-instrument tracking tasks for the subject to perform while he is experiencing orientational illusions but is not actually controlling the motion of the trainer. The temptation is very strong for unsophisticated operating personnel to tell the subject he is

"fighting disorientation" if he performs well on the tracking task while subjected to the illusion-generating motions. Because the subject's real orientation is irrelevant to the tracking task, any orientational illusion is also irrelevant, and he experiences no conflict between visual and vestibular information in acquiring cues upon which to base his control responses. This situation, of course, does not capture the essence of disorientation in flight; and the trainee who is led to believe he is fighting disorientation in such a ground-based demonstration may develop a false sense of security about his ability to combat disorientation in flight. The increasing use of spatial disorientation demonstrators, in which the subject must control the actual motion of the trainer by referring to true-reading instruments while under the influence of orientational illusions, will most likely reduce the potential for misuse and will improve the effectiveness of presentations to pilots on the subject of spatial disorientation.

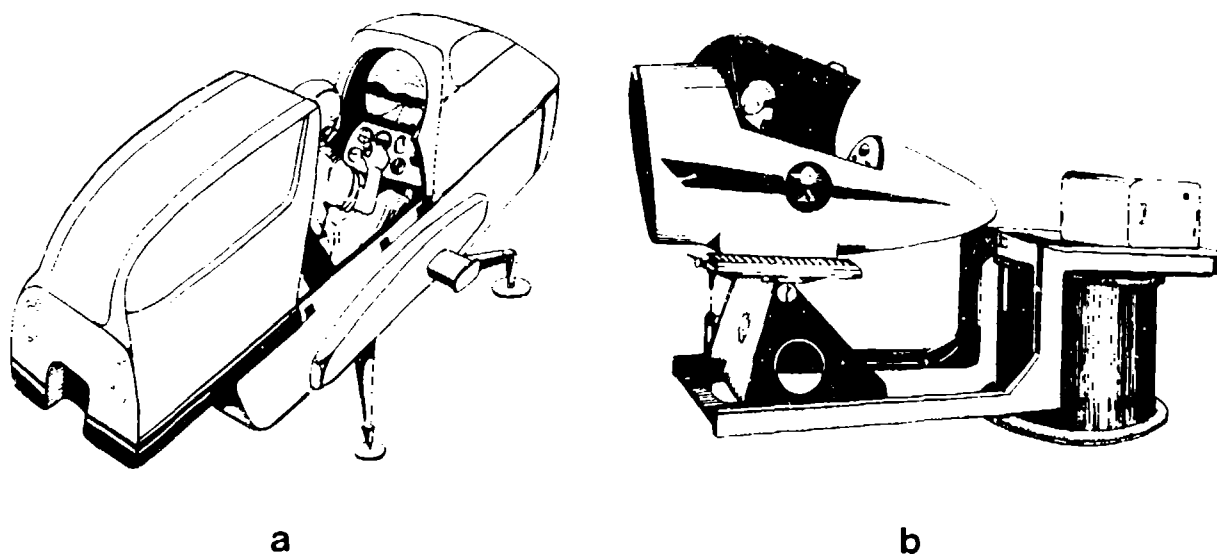


Figure 38. Two types of antivertigo trainer currently in use: a. The Vertigon®, an orientational illusion demonstrator, allows the subject to experience Coriolis and somatogyral illusions while performing tracking and dial-setting tasks. b. The Vertifuge®, a spatial disorientation demonstrator, subjects the trainee to somatogravic, Coriolis, and somatogyral illusions that generate orientational conflicts as he tries to control the attitude and motion of the device by referring to a true-reading attitude indicator.

Flight training provides a good opportunity to instruct pilots about the hazards of spatial disorientation. Inflight demonstrations of vestibular illusions are included in most formalized pilot training curricula, although the efficacy of such demonstrations is highly dependent on the motivation and skill of the individual flight instructor. Somatogyral and somatogравic illusions and illusions of roll attitude can usually be induced in a student pilot by a flight instructor who either understands how the vestibular system works or knows from experience which maneuvers consistently produce illusions. The vestibular-illusion demonstrations should not be confused with the unusual-attitude-recovery demonstrations in the typical pilot training syllabus: the objective of the former is for the student to experience orientational illusions and recognize them as such; that of the latter is for the student to learn to regain control of an aircraft in a safe and expeditious manner. In both types of demonstration, however, control of the aircraft should be handed over to the student pilot with the instruction, "Make the instruments read right."

Part of flight training is continuing practice to maintain flying proficiency, and the importance of such practice in reducing the likelihood of having a disorientation mishap cannot be overemphasized. Whether flying on instruments, in formation, or engaged in aerobatic maneuvering, familiarity with the environment--based on recent exposure to it--and proficiency at the flying task--based on recent practice at it--result not only in a greater ability to avoid or dispel orientational illusions, but also in a greater ability to cope with disorientation when it does occur.

Inflight Procedures. If a particular inflight procedure frequently results in spatial disorientation, it stands to reason that modifying or eliminating that procedure should help reduce aircraft mishaps due to disorientation. Night formation takeoffs and rejoins are examples of inflight procedures that very frequently are associated with spatial disorientation; and the United States Air Force has, wisely, officially discouraged these practices in most of its major commands.

Another area of concern is the "lost wingman" procedure, used when a pilot has lost sight of the aircraft on which he has been flying wing. Usually the loss of visual contact is due to poor visibility, and occurs after a period of vacillation between formation flying and instrument flying. Such conditions, of course, invite disorientation. The lost wingman procedure must, therefore, be made as uncomplicated as possible while still allowing safe separation from the other elements of the flight. Maintaining a specified altitude and heading away from the flight until further notice is an ideal lost wingman procedure, in that it avoids frequent or prolonged disorientation-inducing turns and minimizes cognitive workload. Often a pilot flying wing in bad weather does not lose sight of the lead aircraft, but suffers so much disorientation stress as to make

the option of going lost wingman seem safer than that of continuing in the formation. A common practice in this situation is for the wingman to take the lead position in the formation, at least until the disorientation disappears. This avoids the necessity of having the disoriented pilot make a turn away from the flight to go lost wingman, which could be especially difficult and dangerous because of his disorientation. One should question the wisdom of having a disoriented pilot leading a flight, however; and some experts in the field of spatial disorientation are adamantly opposed to this practice, with good reason.

Verbal communication between pilots can help prevent disorientation. In formation flight in weather, for example, it is good practice for the flight leader to inform his wingman periodically of the attitude, altitude, airspeed and heading of the flight, as the task of formation flying makes it difficult for the wingman to obtain accurate orientation information by monitoring flight instruments. In some cases a copilot or other crew member is available to monitor aircraft attitude, motion, and position during times when the pilot is fully occupied with other demanding tasks (e.g., weapons delivery at night). The other crew member's verbal orientational status reports or warnings of hazardous orientations can serve the pilot well under such circumstances.

The manner in which others communicate with the pilot who is disoriented can mean the difference between life and death for that pilot and his passengers. Unfortunately, no clear-cut procedure exists for ensuring appropriate communications to a disoriented pilot. Should he be hounded mercilessly with verbal orders to get on the instruments, or should he be left relatively undistracted to solve his orientation problems? The extremes of harassment and neglect are definitely not appropriate; a few forceful, specific, action-oriented commands probably represent the best approach. "Level the artificial horizon!" and "Roll right 90 degrees!" are examples of such commands. One must remember that the pilot suffering from spatial disorientation may be either so busy or so functionally compromised that friendly chit-chat or complex instructions may fall on deaf ears. Simple, emphatic directions may be the only means of penetrating the disoriented pilot's consciousness.

To illustrate how official recommendations regarding inflight procedures are disseminated to pilots in an effort to prevent spatial disorientation mishaps, a message from a major United States Air Force command headquarters to field units is excerpted here:

"...Review SD procedures in [various Air Force manuals]... Discuss the potential for SD during flight briefings prior to flight involving night, weather, or conditions where visibility is significantly reduced... Recognize the [SD] problem early and initiate corrective actions before aircraft control is compromised.

A. Single Ship:

(1) Keep the head in the cockpit. Concentrate on flying basic instruments with frequent reference to the attitude indicator. Defer non-essential cockpit chores.

(2) If symptoms persist, bring aircraft to straight and level flight using the attitude indicator. Maintain straight and level flight until symptoms abate--usually 30 to 60 seconds. Use autopilot if necessary.

(3) If necessary, declare an emergency and advise air traffic control. Note: it is possible for SD to proceed to the point where the pilot is unable to see, interpret, or process information from the flight instruments. Aircraft control in such a situation is impossible. A pilot must recognize when physiological/psychological limits have been exceeded and be prepared to abandon the aircraft.

B. Formation flights:

(1) Separate aircraft from the formation under controlled conditions if the weather encountered is either too dense or turbulent to insure safe flight.

(2) A flight lead with SD will advise his wingmen that he has SD and he will comply with procedures in Paragraph A. If possible, wingmen should confirm straight and level attitude and provide verbal feedback to lead. If symptoms do not abate in a reasonable time, terminate the mission and recover the flight by the simplest and safest means possible.

(3) Two-ship formation. Wingman will advise lead when he experiences significant SD symptoms.

(a) Lead will advise wingman of aircraft attitude, altitude, heading, and airspeed.

(b) The wingman will advise lead if problems persist. If so, lead will establish straight and level flight for at least 30 to 60 seconds.

(c) If the above procedures are not effective, lead should transfer the flight lead position to the wingman while in straight and level flight. Once assuming lead, maintain straight and level flight for 60 seconds. If necessary, terminate the mission and recover by the simplest and safest means possible.

(4) More than two-ship situation. Lead should separate the flight into elements to more effectively handle a wingman with persistent SD symptoms. Establish straight and level flight. The element with the SD pilot will remain straight and level while other element separates from the flight."

Cockpit Layout and Flight Instruments. One of the most notorious vertigo traps is the communications-transceiver frequency selector or transponder code selector located in an obscure part of the cockpit: to manipulate this selector requires the pilot not only to look away from his flight instruments, thus interrupting his instrument scan, but also to tilt his head to view the readout, thus potentially subjecting him to a Coriolis or G-excess illusion. Aircraft designers are now aware that easy accessibility and viewing of such frequently used devices minimize the potential for spatial disorientation; accordingly, most modern aircraft have communications frequency and transponder code selectors and readouts located in front of the pilot near the flight instruments.

The location of the flight instruments themselves is also very important: they should be clustered directly in front of the pilot, and the attitude indicator--the primary provider of orientation cueing and the primary instrument by which the aircraft is controlled--should be in the center of the cluster (Fig. 39). When this principle is not respected, the potential for spatial disorientation is increased. A certain modern fighter aircraft, for example, was designed to have the pilot sitting high in the cockpit to enhance his field of view during air-to-air combat in conditions of good visibility. This design relegated the attitude indicator to a position more or less between the pilot's knees. As a result, at night and during instrument weather, the pilot is subjected to potentially

disorienting peripheral visual motion and position cueing by virtue of his being surrounded by a vast expanse of canopy, while he tries to glean with central vision the correct orientation information from a relatively small, distant attitude indicator. The net effect is an unusually difficult orientation problem for the pilot, and a greater risk of developing spatial disorientation in this aircraft than in others with a larger and more advantageously located attitude indicator.

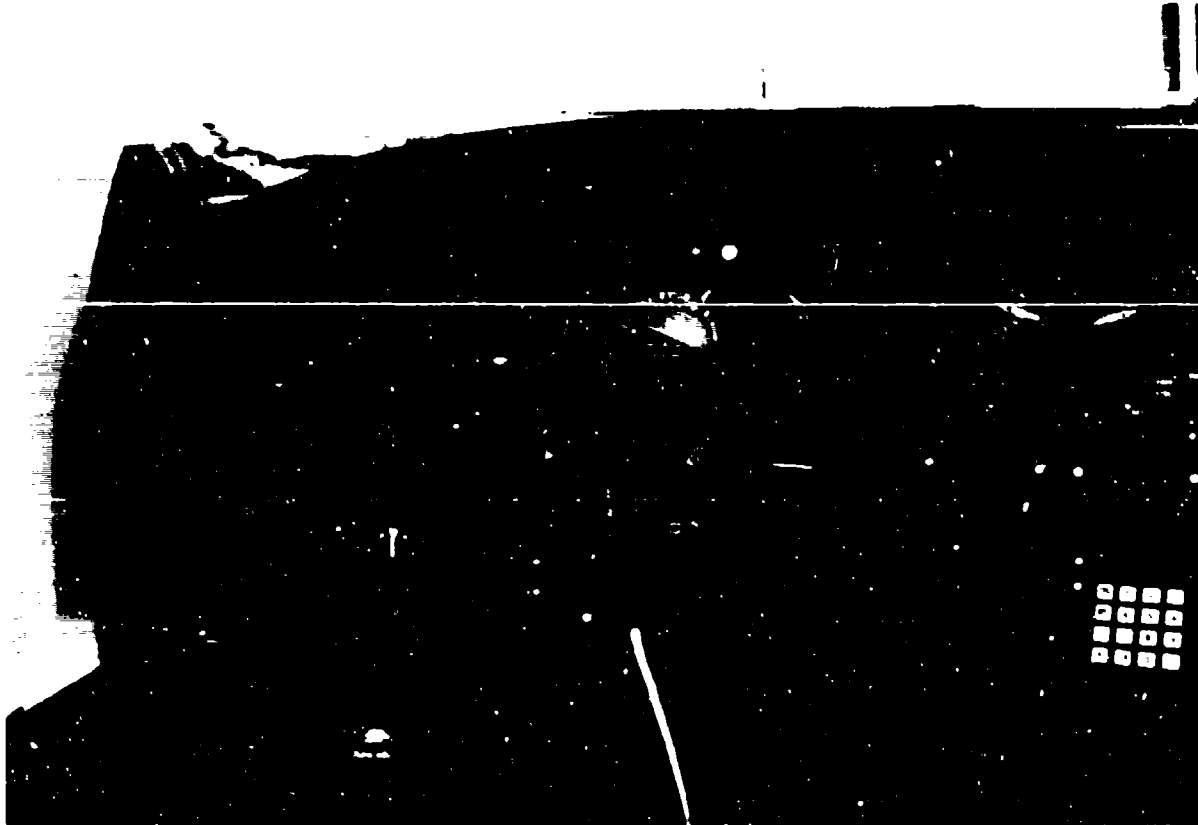


Figure 39. A well-designed instrument panel, with the attitude indicator located directly in front of the pilot, and the other flight instruments clustered around it. Radios and other equipment requiring frequent manipulation and viewing are placed close to the flight instruments to minimize interruption of the pilot's instrument scan and to obviate his having to make head movements that could precipitate spatial disorientation. (Photo courtesy of Gen-Aero, Inc., San Antonio, TX.)

The verisimilitude of the flight instruments is also a major factor in their ability to convey readily assimilable orientation information. The old "needle, ball, and airspeed"

indicators (a needle pointer showing the direction and rate of turn, a ball showing whether the turn is being properly coordinated with the rudders, and an airspeed indicator showing whether the airplane is climbing or diving) required a lot of interpretation for the pilot to perceive his spatial orientation through them; nevertheless, this combination sufficed for nearly a generation of pilots. When the attitude indicator (also known as the gyro horizon, artificial horizon, or attitude gyro) was introduced, it greatly reduced the amount of work required to spatially orient during instrument flying because the pilot could readily imagine the artificial horizon line to be the real horizon. In addition to becoming more reliable and more versatile over the years, it became even easier to interpret: the face was divided into a gray or blue "sky" half and a black or brown "ground" half, with some models even having lines of perspective converging to a vanishing point in the lower half. Such a high degree of similarity to the real world has made the attitude indicator the mainstay of instrument flying today.

A relatively new concept in flight instrumentation, the head-up display (HUD), projects numeric and other symbolic information to the pilot from a combining glass near the windscreen, so he can be looking forward out of the cockpit and simultaneously monitoring flight and weapons data. When the pilot selects the appropriate display mode, pitch and roll attitude of the aircraft are observed on the "pitch ladder" (Fig. 40) and heading, altitude, airspeed, and other flight parameters are numerically displayed elsewhere on the HUD. Its up-front location and its close-together arrangement of most of the required aircraft control and performance data make the HUD an attractive alternative to the conventional cluster of instruments, and some pilots use the HUD as the primary instrument for spatial orientation and aircraft control during instrument flight. Pilots' acceptance and use of the HUD for flying in instrument weather has not been universal, however: many prefer to use the HUD under conditions of good outside visibility and use the conventional instruments for flying at night and in weather. The reason for this preference may be that the horizon on the conventional instrument looks more like the natural horizon than does the zero-pitch indicator on the HUD pitch ladder. Another reason may be that the HUD presents such a narrow view of the outside world--a "vernier" view with high resolution--while the conventional attitude indicator gives an expansive pictorial view of the spatial environment. Furthermore, the relative instability of the HUD pitch ladder and the tendency for the zero-pitch line to disappear from view make the HUD somewhat difficult to use during moderately active maneuvering, as would be necessary during an unusual-attitude recovery attempt.

As good as they are, both the attitude indicator and the HUD leave much to be desired as flight instruments for assuring spatial orientation. Both suffer from the basic design deficiency of presenting visual spatial orientation information to

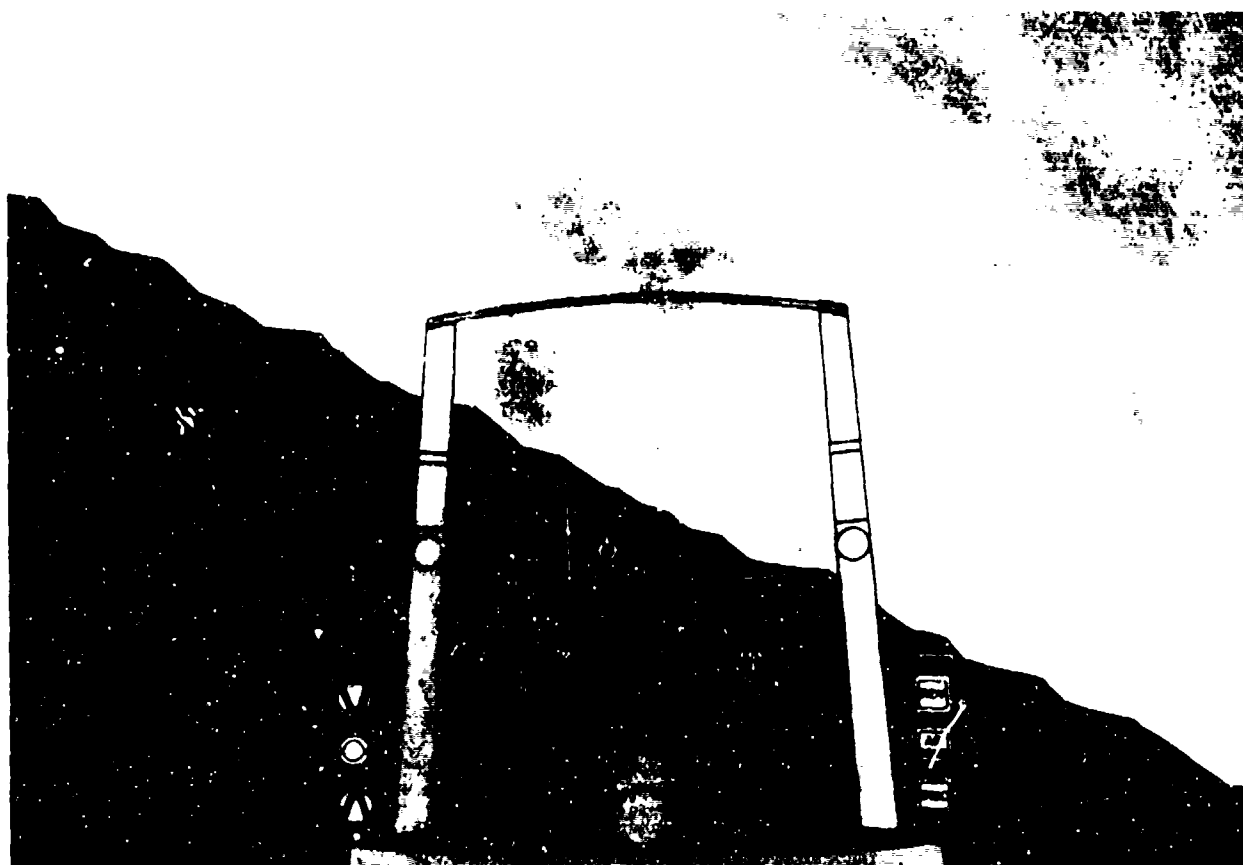


Figure 40. A typical head-up display (HUD). The pitch ladder in the center of the display provides pitch and roll attitude information.

the wrong sensory system--the focal visual system. Two untoward effects result. First, the pilot's focal vision not only must serve to discriminate numerical data from a number of instruments, but also must take on the task of spatially orienting the pilot. The pilot thus has to employ his focal visual system in a somewhat inefficient manner during instrument flight, with about 70% of his time spent viewing the attitude indicator, while his ambient vision remains unutilized. Second, the fact that focal vision is not naturally equipped to provide primary spatial orientation cues causes pilots difficulty in interpreting the artificial horizon directly: there is a tendency, especially among novice pilots, to sense backwards the displayed deviations in roll and pitch, and to make initial roll and pitch corrections in the wrong direction. Several approaches have been taken to try to improve the efficiency of the pilot's acquisition of orientation information from the attitude indicator and associated flight instruments. One has been to make the artificial horizon stationary but to roll and pitch the small aircraft on the instrument to indicate the motion of the real aircraft (the

so-called "outside-in" presentation, as opposed to the "inside-out" presentation of conventional attitude indicators). Theoretically, this configuration relieves the pilot of having to spatially orient himself before trying to fly the aircraft: the pilot merely flies the small aircraft on the attitude instrument and the real aircraft follows, so to speak. Another approach involves letting the artificial horizon provide pitch information, but having the small aircraft on the attitude instrument provide roll information, and collocating heading, vertical velocity, airspeed, throttle setting, and navigation parameters with the aircraft attitude information on a 7-cm instrument face. Such an instrument is the Crane Alweather Flitegage® (Fig. 41). Neither of these approaches, however, frees foveal vision from the unnatural task of processing spatial orientation information. Another concept, the peripheral visual horizon display (PVHD), also known as the Malcolm horizon, attempts to give pitch and roll cues to the pilot through his paracentral and peripheral vision, thus sparing foveal vision for tasks requiring a high degree of visual discrimination (44,45). The several varieties of PVHD that have been developed project across the instrument panel a long, thin line of light representing the true horizon, which line of light moves directly in accordance with the relative movement of the true horizon (Fig. 42). The potential

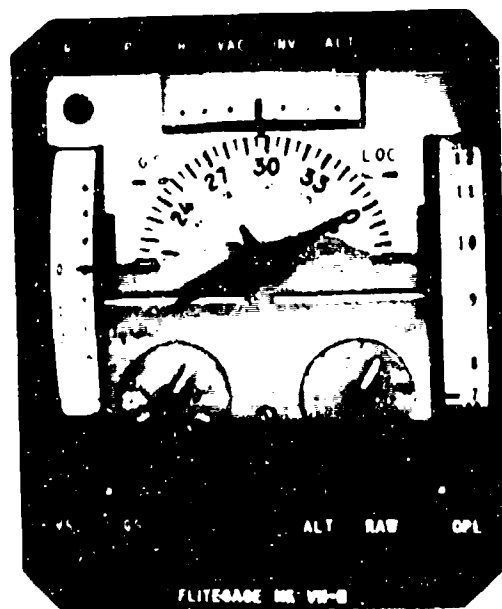


Figure 41. The Crane Alweather Flitegage®. The artificial horizon provides pitch information in the usual manner, but the small airplane on the instrument rolls in accordance with the rolling motion of the real aircraft. Other important flight data are displayed on the instrument face, thus minimizing the work involved in the crosscheck.

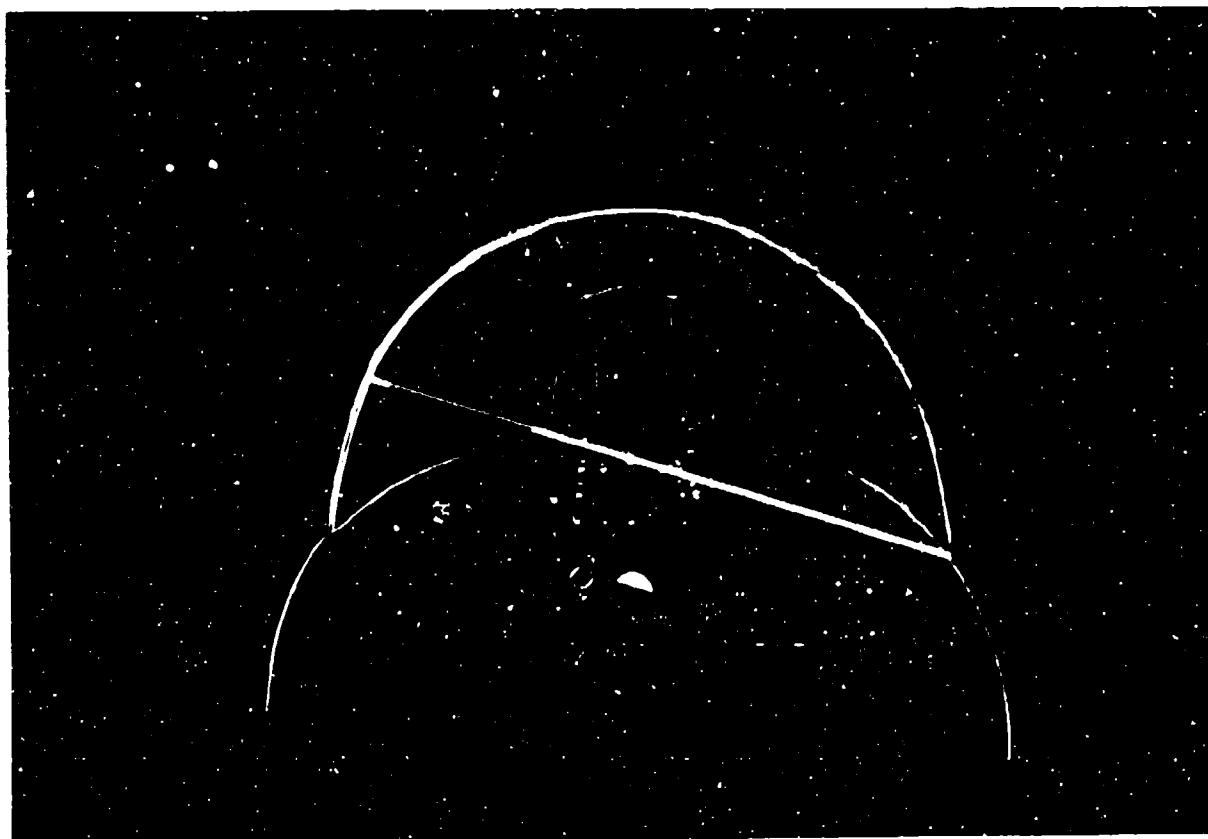


Figure 42. The peripheral visual horizon display (PVHD), or Malcolm horizon. An artificial horizon projected across the instrument panel moves in accordance with the real horizon, and the pilot observes the projected horizon and its movement with his peripheral vision. Theoretically, this enables him to process spatial orientation information in the natural fashion, and spares his foveal vision for tasks requiring a high degree of visual discrimination.

for further development and eventual pilot acceptance of PVHD-type aircraft attitude displays appears good, as the PVHD is based on the physiologically sound concept of providing primary spatial orientation cueing through ambient vision--i.e., in the natural fashion.

Other Sensory Phenomena

Flicker vertigo, fascination, and target hypnosis are traditionally described in conjunction with spatial disorientation--even though, strictly speaking, these entities involve alterations of attention rather than aberrations of perception. Nor

is the breakoff phenomenon related directly to spatial disorientation, but the unusual sensory manifestations of this condition make our discussion of it here seem appropriate.

Flicker Vertigo. As most people are aware from personal experience, viewing a flickering light or scene can be distracting, annoying, or both. In aviation, flicker is sometimes created by helicopter rotors or idling airplane propellers interrupting direct sunlight, or less frequently by such things as several anticollision lights flashing in nonunison. Pilots report that such conditions are indeed a source of irritation and distraction, but there is little evidence that flicker induces either spatial disorientation or clinical vertigo in normal aircrew. In fact, one authority insists there is no such thing as flicker vertigo and that the original reference to it was merely speculation (46). Certainly, helicopter rotors or rotating beacons on aircraft can produce angular vection illusions because they create revolving shadows or revolving areas of illumination; but vection does not result from flicker. Symptoms of motion sickness also can conceivably result from the sensory conflict associated with angular vection; but again, these symptoms would be produced by revolving lights and shadows, not by flicker.

Nevertheless, one should be aware that photic stimuli at frequencies in the 8- to 14-Hz range, that of the electroencephalographic alpha rhythm, can produce seizures in those rare individuals who are susceptible to flicker-induced epilepsy. Although the prevalence of this condition is very low (less than 0.00005), and the number of pilots affected are very few, some helicopter crashes are thought to have been caused by pilots suffering from flicker-induced epilepsy.

Fascination. Coning of attention is something everyone experiences every day, but it is especially likely to occur when we are stressed by the learning of new skills or by the relearning of old ones. Pilots are apt to concentrate on one particular aspect of the flying task, to the relative exclusion of others, when that aspect is novel or unusually demanding. If this concentration is of such a degree as to cause the pilot to disregard important information to which he should respond, it is termed fascination. An extreme example of fascination is that in which the pilot becomes so intent on delivering weapons to the target that he ignores the obvious cues of ground proximity and flies into the ground. Mishaps of this sort are said to result from target hypnosis; no actual hypnotic process is suspected or should be inferred, however. Other examples of fascination in aviation are: the monitoring of one flight instrument rather than cross-checking during particularly stressful instrument flight; paying so much attention to flying precise formation that other duties are neglected; and the aviator's most ignominious act of negligence, landing an airplane with the landing gear up, despite the clearly perceived warning from the gear-up warning horn. These examples help us appreciate

the meaning of the original definition of fascination by Clark et al. (47): "a condition in which the pilot fails to respond adequately to a clearly defined stimulus situation in spite of the fact that all the necessary cues are present for a proper response and the correct procedure is well known to him." From the definition and the examples given, we can see that fascination can involve either a sensory deficiency or an inability to act, or perhaps both. We also know that fascination--at least the type involving sensory deficiency--occurs not only under conditions of relatively high workload, but also can occur when workload is greatly reduced and tedium prevails. Finally, the reader should understand that coning of attention, as occurs with fascination, is not the same thing as tunneling of vision, which occurs with G stress: even if all pertinent sensory cues could be made accessible to foveal vision, the attentional lapses associated with fascination could still prevent those cues from being perceived or eliciting a response.

Breakoff. Clark and Graybiel (48) reported in 1957 a condition perhaps best described by the title of their paper: "The Breakoff Phenomenon--A Feeling of Separation from the Earth Experienced by Pilots at High Altitude." They found that 35% of 137 United States Navy and Marine Corps jet pilots interviewed by them had had feelings of being detached, isolated, or physically separated from the earth when flying at high altitudes. The three conditions most frequently associated with the experience were high altitude (5000 to 15,000 m, with a median of 10,000 m), being alone in the aircraft, and not being particularly busy with operating the aircraft. The majority of the pilots interviewed found the breakoff experience exhilarating, peaceful, or otherwise pleasant; over a third, however, felt anxious, lonely, or insecure. No operational importance could be ascribed to the breakoff phenomenon; specifically, it was not considered to have a significant effect on a pilot's ability to operate his aircraft. The authors nevertheless suggested that the breakoff experience might precipitate significant effects on a pilot's performance when coupled with preexisting anxiety or fear, and for that reason the phenomenon should be described to pilots before they go alone to high altitudes for the first time. Breakoff may, on the other hand, have a profound, positive effect on motivation to fly. Who could deny the importance of this experience to John Gillespie Magee, Jr., who gave us "High Flight," the most memorable poem in aviation?

"On, I have slipped the surly bonds of earth...
Put out my hand, and touched the face of God."

MOTION SICKNESS

Motion sickness is a perennial aeromedical problem. This important syndrome is discussed here to emphasize the critical importance of the spatial orientation senses in its pathogenesis. So closely entwined, in fact, are the mechanisms of spatial orientation and those of motion sickness, that orientation sickness is sometimes (and legitimately) used as the general term for the category of related conditions that we commonly refer to as motion sickness.

Definition, Description, and Significance of Motion Sickness

Motion sickness is a state of diminished health characterized by specific symptoms that occur in conjunction with, and in response to, unaccustomed conditions existing in one's motional environment. These symptoms usually progress from lethargy, apathy, and stomach awareness to nausea, pallor, and cold eccrine perspiration, then to retching and vomiting, and finally to total prostration if measures are not taken to arrest the progression. The sequence of these major symptoms is sufficiently predictable that vestibular scientists have devised a commonly used scale, consisting of five steps from Malaise I through Frank Sickness, to quantify the severity of motion sickness according to the level of symptoms manifested (49). Other symptoms sometimes seen with motion sickness are headache, increased salivation and swallowing, decreased appetite, eructation, flatulence, and feeling warm. Although vomiting sometimes provides temporary relief from the symptoms of motion sickness, more commonly the motion-sick individual will continue to be sick if the offending motion or other condition to which he is not accustomed continues, and the vomiting will be replaced by nonproductive retching, or "dry heaves." A wide variety of motions and orientation conditions qualify as offensive, so there are many species of the generic term, "motion sickness." Among them are seasickness, airsickness, car sickness, train sickness, amusement-park-ride sickness, camel sickness, motion picture sickness, flight simulator sickness, and the most recent addition to the list: space sickness.

Military Experience. Armstrong (50) provides us with some interesting statistics on airsickness associated with the World War II military effort:

"It was learned that 10 to 11 percent of all flying students became airsick during their first 10 flights, and that 1 to 2 percent of them were eliminated from flying training for that reason. Other aircrew members in training had even greater difficulty and the

airsickness rate among them ran as high as 50 percent in some cases. It was also found that fully trained combat crews, other than pilots, sometimes [developed airsickness] which affected their combat efficiency. An even more serious situation was found to exist among airborne troops. Under very unfavorable conditions, as high as 70 percent of these individuals became airsick and upon landing were more or less temporarily disabled at a time when their services were most urgently needed."

More recent studies of the incidence of airsickness in United States and British military flight training reveal that approximately 40% of aircrew trainees become airsick at some time during their training. In student pilots there is a 15% to 18% incidence of motion sickness severe enough to interfere with control of the aircraft. Airsickness in student aviators occurs almost exclusively during the first several training flights, during spin training, and during the first dual aerobatic flights. The adaptation of which most people are capable is evidenced in the fact that only about 1% of military pilot trainees are eliminated from flying training because of intractable airsickness. The percentage of other aircrew trainees eliminated because of airsickness is considerably higher, however.

Although trained pilots almost never become airsick while flying the aircraft themselves, they surely can become sick while riding as copilot or as a passenger. Other trained aircrew, such as navigators and weapon systems operators, are likewise susceptible to airsickness. Particularly provocative for these aircrew are flights in turbulent weather, low-level "terrain-following" flights, and flights in which high G forces are repeatedly experienced, as in air combat training and bombing practice. Both the lack of foreknowledge of aircraft motion, which results from not having primary control of the aircraft, and the lack of a constant view of the external world, which results from having duties involving the monitoring of in-cockpit displays, are significant factors in the development of airsickness in these aircrew.

Not surprisingly, seasickness is a hazard to aircrew who bail out over water. A life raft bobbing in the ocean provides a notoriously provocative stimulus for seasickness; in one study three-fourths of the subjects became seasick and over half vomited during one hour of exposure to artificial wave motion while riding in a life raft (51). The debilitating and demoralizing effect of seasickness on the ability and will of downed aircrew to survive should be considered when planning sea rescue operations.

Flight simulator sickness is getting increased attention now as aircrew spend more and more time in flight simulators capable of ever greater realism. Interestingly, simulator sickness is more likely to occur in pilots having considerable experience in the aircraft which the simulator is simulating than in pilots without such experience. The symptoms of simulator sickness are for the most part those of the other forms of motion sickness, with nausea occurring in over 70% of pilots flying certain simulators (52). Progression of symptoms to the point of vomiting is uncommon in simulator sickness, however. Simulators providing wide-field-of-view visual presentations are reported to produce the additional symptoms of kinesthetic aftereffects, involuntary visual flashbacks, and disturbances of balance and locomotion for up to 10 hr after exposure (52). For that reason it is recommended that pilots get a good night's sleep before flying real aircraft again after training intensively in wide-field-of-view flight simulators.

Civil Experience. The incidence of airsickness in flight training of civilians can only be estimated, but is probably somewhat less than that for their military counterparts because the training of civil pilots usually does not include spins or other aerobatics. Fewer than 1% of passengers in today's commercial air transport aircraft become airsick, largely because the altitudes at which these aircraft generally fly are usually free of turbulence. This cannot be said, however, for passengers of most of the lighter, less capable, general aviation aircraft, who often must spend considerable portions of their flights at the lower, "bumpier" altitudes.

Space Sickness. The challenge of space flight includes coping with space sickness, a form of motion sickness experienced first by cosmonaut Titov and subsequently by approximately 29% of spacecrew (46 out of 157, as of this writing). The incidence of sickness aboard the more recently launched, larger spacecraft is even greater (43%). We must therefore acknowledge the potential impact of space sickness on manned space operations and hope that its impact will be minimized by appropriate mission planning. The sheer expense associated with each space launch, the high task loading of spacecrew, and the relative irrevocability of each space mission once committed, make space sickness a hazard of primary importance.

If the duration of a space mission is long enough to allow crewmembers to adapt to the motional environment of space, they also risk disadapting to that of earth, and can consequently suffer earth sickness upon returning from the zero-G to the 1-G condition. Another type of space sickness will be encountered in the event that large space stations are rotated to generate G loading for the purpose of alleviating the fluid shift, cardiovascular deconditioning, and skeletal demineralization that occur in the zero-G environment. Vestibular Coriolis effects created in occupants of such rotating systems are very potent producers of motion sickness, and would be expected to plague

the occupants for several days after arrival. Again, to the extent they were to adapt to the rotating environment, they would risk disadapting to the nonrotating one, and would suffer from motion sickness upon leaving the rotating space station.

Etiology

Man has speculated about the causes of and reasons for motion sickness for thousands of years. Largely because of the scientific interest in motion sickness that has been generated by naval and aerospace activities of the present century, we may now have a satisfactory explanation for this puzzling malady.

Correlating Factors. As already mentioned, motion sickness occurs in response to conditions to which one is not accustomed existing in his motional environment. By "motional environment" we mean all of the linear and angular positions, velocities, and accelerations that are directly sensed or secondarily perceived by an individual as determining spatial orientation. The primary quantities of relevance here are mechanically (as opposed to visually) perceived linear and angular accelerations--those stimuli that act on the vestibular end-organs. Certainly the pitching, rolling, heaving, and surging motions of ships in bad weather are clearly correlated with motion sickness, as are the pitching, rolling, yawing, and positive and negative G-pulling of aircraft during maneuvering. Abnormal stimulation of the semicircular ducts alone, as with a rotating chair, can result in motion sickness. So also can abnormal stimulation of the otolith organs alone, as occurs in an elevator or a four-pole swing. Whether the stimulation provided is complex, as is usually the case on ships and in aircraft, or simple, as generated in the laboratory, the important point is that abnormal labyrinthine stimulation is associated with the production of motion sickness. Not only is a modicum of abnormal vestibular stimulation sufficient to cause motion sickness, but some amount of vestibular stimulation is also necessary for motion sickness to occur: labyrinthectomized experimental animals, and humans without functioning vestibular end-organs (so-called "labyrinthine defectives") are completely immune to motion sickness.

The visual system can play two very important roles in the production of motion sickness. First, motion sensed solely through vision can make some people sick. Examples of this phenomenon are: motion picture sickness, in which wide-screen movies of rides on airplanes, roller-coasters, and ships in rough seas are provocative; microscope sickness, in which susceptible individuals cannot tolerate viewing moving microscope slides; and flight simulator sickness, in which wide-field-of-view visual motion systems create motion sickness in the absence of any mechanical motion. Abnormal stimulation of ambient (peripheral) vision rather than focal (foveal) vision appears to be the salient feature of visually induced motion sickness. The fact that orientation information processed through the ambient visual system converges on the vestibular nuclei makes visually

induced motion sickness less mysterious a phenomenon, even if not totally explicable. The second role of vision in the etiology of motion sickness is illustrated by the well-known fact that absence of an outside visual reference makes persons undergoing abnormal motion more likely to become sick than they would be if an outside visual reference were available. Cases in point: the sailor who becomes sick below deck but prevents the progression of motion sickness by coming topside to view the horizon, and the aircrewman who becomes sick while attending to duties inside the aircraft (e.g., radarscope monitoring) but alleviates symptoms by looking outside.

Other sensory systems capable of providing spatial orientational information are also capable of providing avenues for motion-sickness-producing stimuli. The auditory system, when stimulated by a revolving sound source, is responsible for audiogenic vertigo, audiokinetic nystagmus, and concomitant symptoms of motion sickness. Nonvestibular proprioceptors may contribute to the development of motion sickness when the pattern of stimulation of these senses by linear and angular accelerations is unfamiliar. But perhaps more important than the actual sensory channel employed or the actual pattern of stimulation delivered is the degree to which the spatial orientational information received deviates from that anticipated. The experience with motion sickness in various flight simulators bears witness to the importance of unexpected patterns of motion and unfulfilled expectations of motion. Instructor pilots in the 2-FH-2 helicopter hover trainer, for example, were much more likely to become sick in the device than were student pilots (53). It is postulated that imperfections in flight simulation are perceived by pilots who, as a result of their experience in the real aircraft, expect certain orientational stimuli to occur in response to certain control inputs. Pilots without time in the real aircraft, on the other hand, have no such expectations, and therefore notice no deviations from them in the simulator. Another example of the role played by expectation of motion in the generation of motion sickness is seen in the pilot who does not become sick as long as he has control of the airplane, but does become sick when another pilot is flying the same maneuvers in the same airplane. In this case the pilot's expectation of motion is always fulfilled whenever he is controlling the airplane, but is not when someone else is flying.

Several other variables not primarily related to spatial orientation seem to correlate well with motion sickness susceptibility. Age is one: susceptibility increases with age until puberty, then decreases thereafter. Sex is another: women are more susceptible than men at any given age. The personality characteristics of emotional lability and excessive rigidity are also positively correlated with motion sickness susceptibility. Whether one is mentally occupied with a significant task during exposure to motion, or is free to dwell on orientation cues and the state of his stomach, seems to affect his susceptibility--the latter, more introverted state being the more conducive to

motion sickness. Likewise, anxiety, fear, and insecurity, either about one's orientation relative to the ground or about one's likelihood of becoming motion sick, seem to enhance susceptibility. We must be careful, however, to distinguish between sickness caused by anxiety and sickness caused by motion: a paratrooper who vomits in an aircraft while waiting to jump into battle may be suffering either from extreme anxiety or from motion sickness, or both. Finally, we must recognize that many things, such as mechanical stimulation of the viscera and malodorous aircraft compartments, even though they are commonly associated with conditions that result in motion sickness, do not in themselves cause motion sickness.

A mildly interesting but potentially devastating phenomenon is conditioned motion sickness. Just as Pavlov's canine subjects learned to salivate at the sound of a bell, student pilots and other aircrew, with repeated exposure to the conditioning stimulus of sickness-producing aircraft motion, can eventually develop the autonomic response of motion sickness to the conditioned stimulus of being in, or even just seeing, an aircraft (Fig. 43). For this reason it is advisable to initiate aircrew gradually to the abnormal motions of flight, and to provide pharmacologic prophylaxis against motion sickness, if necessary, in the early instructional phases of flight.

Unifying Theory. Current thinking regarding the underlying mechanism of motion sickness has focused on the "sensory conflict" or "neural mismatch" hypothesis, proposed originally by Claremont in 1931 (54). In simple terms, the sensory conflict hypothesis states that motion sickness results when incongruous orientation information is generated by various sensory modalities, one of which must be the vestibular system. In virtually all examples of motion sickness one can, with sufficient scrutiny, identify the sensory conflict involved. Usually the conflict is between the vestibular and visual senses or between the different components of the vestibular system, but conflicts between vestibular and auditory or vestibular and nonvestibular proprioceptive systems are also possible. A clear example of sickness resulting from vestibular-visual conflict is that which occurs when an experimental subject wears reversing prisms over his eyes so that his visual perception of self-motion is exactly opposite in direction to his vestibular perception of it. Another example is motion-picture sickness, the conflict being between visually perceived motion and vestibularly perceived stationarity. Airsickness and seasickness are most often a result of vestibular-visual conflict: the vestibular signals of linear and angular motion are not in agreement with the visual percept of being stationary inside the vehicle. Vestibular-visual conflict need not even be in relation to motion, but can be in relation to static orientation: some people become sick in antigravity houses, which are built in such a way that the visually apparent vertical is quite different from the true

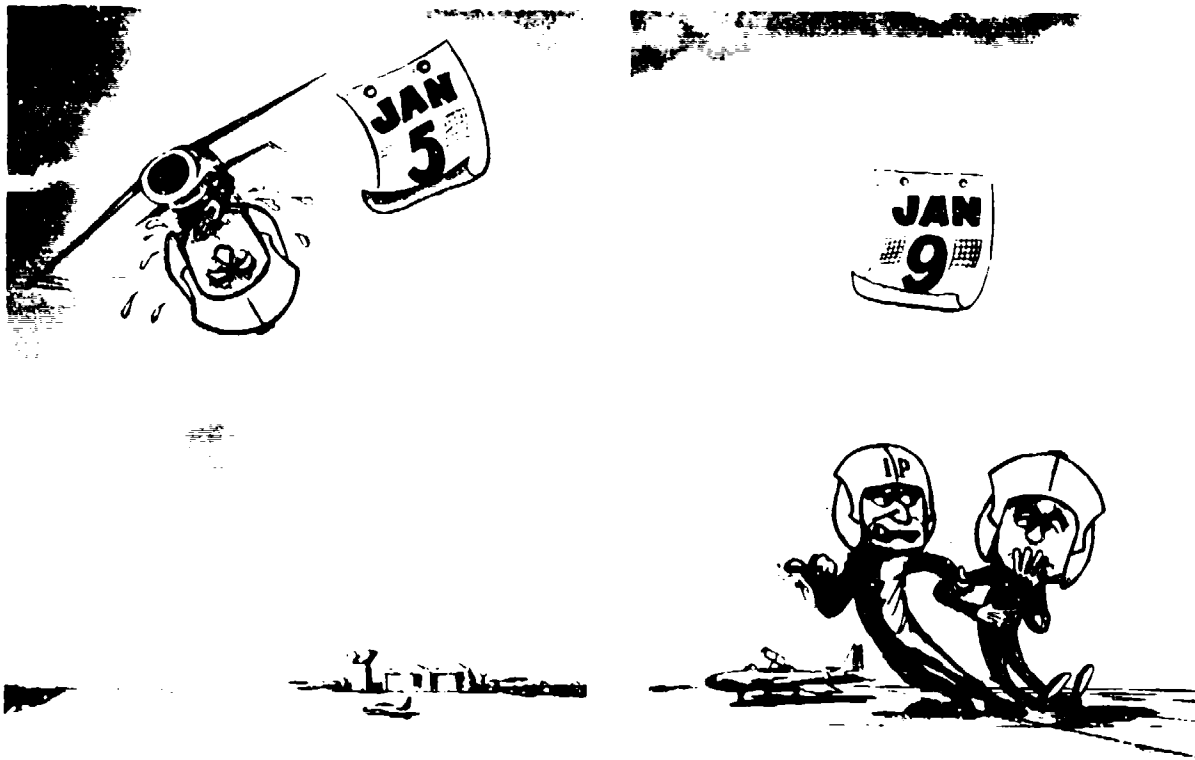


Figure 43. Conditioned motion sickness. A student aviator who repeatedly gets airsick during flight can become conditioned to develop symptoms in response to the sight or smell of an aircraft even before flight. Use of antimotion-sickness medication until the student adapts to the novel motion can prevent conditioned motion sickness.

gravitational vertical. Intravestibular conflict is an especially potent means of producing motion sickness. When vestibular Coriolis effects cause the semicircular ducts to signal falsely that angular velocity about a nonvertical axis is occurring, and the otolith organs do not confirm a resulting change in angular position, the likelihood of developing motion sickness is great. In a zero-gravity environment, when one moves his head up or down the semicircular ducts sense rotation but the otolith organs cannot sense any resulting change of angular position relative to a gravity vector; the generation of this intravestibular conflict is believed to be the underlying mechanism of space sickness. It can also be argued, however, that the sensory conflict responsible for space sickness is between the otolith organs, which detect no gravitational

vertical, and the eyes, to which structures within the space vehicle take on apparent verticality by virtue of some familiar aspect of their configuration.

But what determines whether orientation information is conflicting or not? It is one's prior experience in the motional environment, and the degree to which orientation information expected on the basis of that experience agrees with the actual orientation information received. Thus, according to Reason (55), the important sensory conflict is not so much an absolute discrepancy between information from the several sensory modalities as it is between anticipated and actual orientation information. We see evidence of this in the gradual adaptation to sustained abnormal motional environments such as the sea, space, slow rotation, and the wearing of reversing prisms, and in the readaptation to the normal environment that must take place upon returning to it. We also see that being able to anticipate orientation cues confers immunity to motion sickness, as evidenced by the fact that pilots and automobile drivers almost never make themselves sick, and by the fact that we actively subject ourselves to many motions (jumping, dancing, acrobatics) that would surely make us sick if we were to be subjected to them passively. It appears, then, that the body refers to an internal model of orientational dynamics, both sensory and motor, to effect voluntary and involuntary control over orientation (17). When transient discrepancies between predicted and actual orientation data occur, corrective reflex activity is initiated, or the internal model is updated, or both. But when sustained discrepancies occur, motion sickness is the result.

Teleology. Even if the mechanism of motion sickness could be described completely in terms of cellular and subcellular functions, the question would remain: "What purpose, if any, does motion sickness serve?" The idea that a chance mutation rendered countless generations of vertebrates potential victims of motion sickness, and that the relatively recent arrival of transportation systems gave expression to that otherwise innocuous genetic flaw, strains credulity. Steele has suggested that the symptoms of motion sickness are "caused by cardiovascular inadequacy secondary to diversion of circulating blood to the muscles in response to a threatened need for vigorous muscular action on the basis of inadequately perceived inertial and dynamic environment" (56). A more recent hypothesis, and in our opinion a more satisfying explanation of motion sickness, is that of Treisman (57). He proposed that the orientation senses, in particular the vestibular system, serve an important function in the emetic response to poisons. When an animal ingests a toxic substance and experiences its effects on the central nervous system--namely, deterioration of the finely tuned spatial orientation senses and consequent degraded predictability of sensory responses to motor activity--reflex vomiting occurs and the animal is relieved of the poison. The positive survival value of such a mechanism to eliminate ingested poisons is obvious. The essentiality of the vestibular end-organs and

certain parts of the cerebellum, and the role of sensory conflict as manifested through the functioning of those structures, are provided a rational basis in Treisman's theory. Finally, experimental support for Treisman's theory has been provided by Money and Cheung (58) who found that labyrinthectomized animals, in addition to being immune to motion sickness, exhibit marked impairment of the emetic response to certain naturally occurring poisons.

Prevention and Treatment

The variety of methods at our disposal for preventing and treating motion sickness is less an indication of how easy motion sickness is to control than it is of how incompletely effective each method can be. Nevertheless, logical medical principles are generally applicable; and several specific treatments have survived the test of time and become traditionalized, while some newer approaches appear to have great potential.

Physiologic Prevention. An obvious way to prevent motion sickness is to avoid environments that produce it; but for many individuals in today's world, this is neither possible nor desirable. The most common and ultimately most successful way is to adapt to the novel motional environment through constant or repeated exposure to it. The rapidity with which adaptation occurs is highly variable, depending mainly on the strength of the challenge and on the adaptability of the individual involved. Usually, several days of sustained exposure to mild orientational challenges (like sea and space travel) or several sessions of repeated exposure to vigorous challenges (like aerobatics or centrifuge riding) will confer immunity. The use of antimotion-sickness medications to prevent symptoms during the period of adaptation does not appear to compromise the process of adaptation and is recommended where practicable.

Selection of individuals resistant to motion sickness, or screening out those unusually susceptible to it, has been considered as a method for reducing the likelihood of motion sickness in certain operations, such as military aviation training. The fact that susceptibility to motion sickness is so complex a characteristic makes selection less efficacious a means of prevention than might be supposed. At least three separate factors are involved in motion sickness susceptibility, as identified by Reason and Brand (59): receptivity, the degree to which a given orientational information conflict is perceived and the intensity with which it is experienced and responded to; adaptability, the rate at which one adjusts to a given abnormal orientational environment as evidenced by his becoming less and less symptomatic; and retentivity, the ability to remain adapted to the novel environment after leaving it. These factors appear to be independent. This means a particular prospective aviator with high receptivity might also adapt very rapidly and remain adapted for a long time, so that it would be unwise to eliminate

him from flying training on the basis of a history of motion sickness or even a test of susceptibility. Nevertheless, although the great majority of aircrew trainees do adapt to the aerial environment, use of either vestibular stimulation (60) or a motion sickness questionnaire (61) reveals that sensitivity to motion sickness is inversely related to success in flying training. Furthermore, sound judgment dictates that an attempt to select against crewmembers with a high probability of becoming motion sick is appropriate for some of the more critical and expensive aerospace operations.

Some very promising results have been obtained recently with biofeedback-mediated behavior modification in reducing susceptibility to motion sickness. Cowings and Toscano (62) have reported that subjects receiving autogenic-feedback training (AFT), a biofeedback-based autonomic conditioning procedure, were able to adjust significantly more rapidly to nauseogenic vestibular Coriolis stimulation than were control subjects not provided with AFT. But can biofeedback be used to rehabilitate aircrew suffering from refractory airsickness? Apparently so, as Levy et al. (63) found that the use of relaxation training and biofeedback in the treatment of highly motivated aircrew who were disabled by recurrent airsickness has yielded an 84% rate of return to duty; this rate is substantially better than the 45-50% rate for a comparable group of aircrew not provided the biofeedback treatment.

Physiologic Treatment. Once symptoms of motion sickness have developed, the first step to take to bring about recovery is to escape from the environment producing the symptoms. If this is possible, relief usually follows rapidly; but symptoms can still progress to vomiting, and nausea and drowsiness can sometimes persist for many hours, even after termination of the offending motion. If escape is not possible, assuming a supine position, or just stabilizing the head, seems to offer some relief. As mentioned previously, passengers subjected to motion in enclosed vehicles can help alleviate symptoms by obtaining a view of the natural horizon. One of the most effective physiologic remedies is turning over control of the vehicle to the symptomatic crewmember. Generations of flight instructors have used this technique to avert motion sickness in their students, even though they were probably unable to explain how it works in terms of reducing conflict between anticipated and actual orientation cues. Another procedure which has proved useful in practice is to cool the affected individual with a blast of air from the cabin air vent; such thoughtfulness on the part of their instructors has undoubtedly saved many student pilots from having to clean up the cockpit.

Pharmacologic Prevention. The most effective single medication for prophylaxis against motion sickness is scopolamine (1-hyoscine), 0.3 to 0.6 mg, taken orally 30 min to 1 hr before exposure to motion. Unfortunately, when scopolamine is taken in orally effective doses, the side effects (i.e., drowsiness, dry

mouth, pupillary dilation, and paralyzed visual accommodation) make routine oral administration of this drug to aircrew highly inadvisable. When prophylaxis is needed for prolonged exposure to abnormal motion (e.g., an ocean voyage), oral scopolamine can be administered every 4 to 6 hr; but again, the side effects are troublesome and may preclude repeated oral administration. A novel approach to the problem of prolonged prophylactic administration of scopolamine is the Transderm-Scop® system, in which 0.5 mg of scopolamine is delivered transcutaneously over a 3-day period from a small patch worn on the skin behind the ear. Although the side effects associated with this system of administration are reportedly less than with oral scopolamine, a thorough evaluation of its efficacy has not yet been undertaken.

The antimotion-sickness preparation most commonly used in aircrew is probably the "scope-dex" combination, 0.3-0.6 mg of scopolamine and 5-10 mg of dextroamphetamine, taken orally 1 hr prior to exposure to motion. Not only is this combination more effective than scopolamine alone, but the stimulant effect of the dextroamphetamine counteracts the drowsiness side effect of the scopolamine. Another very useful oral combination is 25 mg each of promethazine and ephedrine, taken approximately 1 hr before exposure. As the individual response to the several effective antimotion-sickness preparations is highly variable, it may be worthwhile to perform individual assessments of different drug combinations and dosages to obtain the maximum benefit. The reader is referred to Graybiel et al. (64) and Johnson et al. (65) for additional information on efficacy of antimotion-sickness preparations.

Pharmacologic Treatment. If motion sickness progresses to the point of nausea, and certainly if to vomiting, oral medication is useless. If the prospect of returning soon to the accustomed motional environment is remote, it is important to treat the condition to prevent the dehydration and electrolyte loss that result from protracted vomiting. Intramuscular injection of scopolamine, 0.3 mg, or promethazine, 25 mg, is recommended. Scopolamine administered intravenously or even by nasal spray or drops is also effective. Promethazine rectal suppositories are used to control vomiting in many clinical situations, and their use in treatment of motion sickness should also be successful. If parenteral administration of scopolamine or promethazine does not provide relief from vomiting, sedation with intravenous phenobarbital may be necessary to prevent progressive deterioration of the patient's condition. Of course, fluid and electrolyte losses must be replaced in patients who have been vomiting for prolonged periods.

Aeromedical Use of Antimotion-sickness Preparations. As mentioned previously, routine use of antimotion-sickness drugs in aircrew is not appropriate because of the undesirable side effects of these drugs. Prophylactic medication can be very useful, however, in helping the student aviator cope with the

novel motions that can cause sickness during flight training--thus promoting better conditions for learning, and preventing the development of conditioned motion sickness. Prophylaxis can also help reduce a student's anxiety over becoming motion sick, which can develop into a self-fulfilling vicious circle. After using medication, if necessary, for two or three dual training sorties--usually at the beginning of flight training and again during the introduction to aerobatics--student pilots should no longer need antimotion-sickness drugs. Use of drugs for solo flight should absolutely be forbidden. A more liberal approach can perhaps be taken with other aircrew trainees, such as navigators, because of their greater propensity to become motion sick and their less critical influence on flight safety. Trained aircrew, as a rule, should not use antimotion-sickness drugs. An exception to this rule is made for spacecrew, whose exposure to the zero-gravity condition of space flight is usually very infrequent, and whose pre-mission adaptation by other means cannot be assured. Spacecrew should also be expected to need prophylaxis for reentry into the normal gravitational environment of the earth after a prolonged stay at zero gravity. Airborne troops, who must arrive at the battle zone fully effective, are also candidates for antimotion-sickness prophylaxis under certain circumstances, such as prolonged low-level flight in choppy weather. In all such cases the flight surgeon must weigh the risks associated with developing motion sickness against the risks associated with the side effects of the antimotion-sickness drugs, and arrive at a judgment of whether or not to medicate.

Thus we see how man's recent transition into the motional environment of aerospace has introduced him not only to new sensations but also to new sensory demands. If he fails to appreciate the fallibility of his natural orientation senses in this novel environment, he succumbs to spatial disorientation. If he recognizes his innate limitations, however, he can meet the demands of the environment and function effectively in it. We see also how man's phylogenetic heritage, by means of orientational mechanisms, renders him susceptible to motion sickness. That same heritage, however, enables him to adapt to new motional environments. The profound and pervasive influence of our orientation senses in aerospace operations cannot be denied or ignored; but through knowledge and understanding, it can be controlled.

REFERENCES

1. Hixson, W.C., Niven, J.I., and Correia, M.J.: Kinematics nomenclature for physiological accelerations, with special reference to vestibular applications. Monograph 14, Naval Aerospace Medical Institute, Pensacola, FL, 1966.
2. Daroff, R.B., and Troost, B.T.: Supranuclear disorders of eye movements. *In* Clinical Ophthalmology, Volume II. Glaser, J. (ed.). New York, Harper and Row, 1976.
3. Henn, V., Young, L.R., and Finley, C.: Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. *Brain Res* 71:144-149, 1974.
4. Dichgans, J., and Brandt, T.: Visual-vestibular interaction: effects on self-motion perception and postural control. *In* Handbook of Sensory Physiology. Volume VIII: Perception. Held, R., Liebowitz, H.W., and Teuber, H.-L. (eds.). Berlin, Springer-Verlag, 1978.
5. Grüsser, O.-J., and Grüsser-Cornehls, U.: Chapter 6. Neuronal mechanisms of visual movement perception and some psychophysical and behavioral correlations. *In* Handbook of Sensory Physiology, Volume VII/3: Central Processing of Visual Information; A: Integrative Functions and Comparative Data. Jung, R. (ed.). Berlin, Springer-Verlag, 1973.
6. Liebowitz, H.W., and Dichgans, J.: The ambient visual system and spatial orientation. *In* Spatial Disorientation in Flight: Current Problems. AGARD-CP-287. NATO/AGARD, Neuilly-sur-Seine, France, 1980.
7. Tredici, T.J.: Visual illusions as a probable cause of aircraft accidents. *In* Spatial Disorientation in Flight: Current Problems. AGARD-CP-287. NATO/AGARD, Neuilly-sur-Seine, France, 1980.
8. Ditchburn, R.W., and Ginsborg, B.L.: Vision with a stabilized retinal image. *Nature* 170:36-37, 1952.
9. Brindley, G.S., and Merton, P.A.: The absence of position sense in the human eye. *J Physiol* 153:127-130, 1960.
10. Sperry, R.W.: Neural basis of the spontaneous optokinetic response preceded by visual inversion. *J Comp Physiol Psych* 43:482-489, 1950.

11. Cohen, M.M.: Chapter 6. Visual-proprioceptive interactions. In Intersensory Perception and Sensory Integration. Walk, R.D., and Pick, H.L., Jr. (eds.). New York, Plenum Publishing Corporation, 1981.
12. Spoendlin, H.H.: Ultrastructural studies of the labyrinth in squirrel monkeys. In The Role of the Vestibular Organs in the Exploration of Space. NASA SP-77, National Aeronautics and Space Administration, Washington, DC, 1965.
13. Jones, G.M.: Disturbance of oculomotor control in flight. Aerospace Med 36:461-465, 1965.
14. Mann, C.W., and Ray, J.: Absolute thresholds of perception of direction of angular acceleration. Joint Proj. Report No. 41, Naval School of Aviation Medicine, Pensacola, FL, May 1956.
15. Meiry, J.L.: The vestibular system and human dynamic space orientation. Doctoral thesis, Massachusetts Institute of Technology, Cambridge, MA, June 1965.
16. Gillingham, K.K.: Training the vestibule for aerospace operations: central control of vestibular function. Military Med 131:696-704, 1966.
17. Oman, C.M.: Space motion sickness and vestibular experiments in Spacelab. SAE Technical Paper 820833, presented at the Twelfth Intersociety Conference on Environmental Systems, San Diego, CA, 19-21 July 1982.
18. Handbook of Sensory Physiology, Volume II: Somatosensory System. Iggo, A. (ed.). Berlin, Springer-Verlag, 1973.
19. Handbook of Sensory Physiology, Volume III/2: Muscle Receptors. Hunt, C.C. (ed.). Berlin, Springer-Verlag, 1974.
20. McIntyre, A.K.: Chapter 3. Central actions of impulses in muscle afferent fibers. In Handbook of Sensory Physiology, Volume III/2: Muscle Receptors. Hunt, C.C. (ed.). Berlin, Springer-Verlag, 1974.
21. Pitts, D.G.: Visual illusions and aircraft accidents. SAM-TR-67-28, USAF School of Aerospace Medicine, Brooks AFB, TX, 1967.
22. Kraft, C.L.: A psychophysical contribution to air safety: simulator studies of visual illusions in night visual approaches. In Psychology--From Research to Practice. Pick, H.L., Jr. et al. (eds.). New York, Plenum Press, 1978.

23. Peters, R.A.: Dynamics of the Vestibular System and Their Relation to Motion Perception, Spatial Disorientation, and Illusions. NASA-CR-1309, National Aeronautics and Space Administration, Washington, DC, 1969.
24. Jones, G.M.: Vestibulo-ocular disorganization in the aerodynamic spin. Aerospace Med 36: 976-983, 1965.
25. Graybiel, A., and Hupp, D.I.: The oculo-gyral illusion: a form of apparent motion which may be observed following stimulation of the semicircular canals. Report No. 4, Naval School of Aviation Medicine, Pensacola, FL, 1945.
26. Gillingham, K.K.: Some notes on the threshold of the vestibular Coriolis effect and its significance to aircrew. SAM-TR-65-55, USAF School of Aerospace Medicine, Brooks AFB, TX, 1965.
27. Cohen, M.M., Crosbie, R.J., and Blackburn, L.H.: Disorienting effects of aircraft catapult launchings. Aerospace Med 44:37-39, 1973.
28. Buley, L.E., and Spelina, J.: Physiological and psychological factors in "the dark night takeoff accident." Aerospace Med 41:553-556, 1970.
29. Martin, J.F., and Jones, G.M.: Theoretical man-machine interaction which might lead to loss of aircraft control. Aerospace Med 36:713-716, 1965.
30. Malcolm, R., and Money, K.E.: Two specific kinds of disorientation incidents: jet upset and giant hand. In The Disorientation Incident. AGARD-CP-95-Part 1. Benson, A.J. (ed.). NATO/AGARD, Neuilly-sur-Seine, France, 1972.
31. Gilson, R.D., et al.: Observations on perceived changes in aircraft attitude attending head movements made in a 2-G bank and turn. Aerospace Med 44:90-92, 1973.
32. Graybiel, A.: Oculogravic illusion. Arch Ophthal 48:605-615, 1952.
33. Nuttall, J.B., and Sanford, W.G.: Spatial disorientation in operational flying. Publication M-27-56, USAF Directorate of Flight Safety Research, Norton AFB, CA, 12 Sep 1956.
34. Moser, R.: Spatial disorientation as a factor in accidents in an operational command. Aerospace Med 40:174-176, 1969.
35. Barnum, F., and Bonner, R.H.: Epidemiology of USAF spatial disorientation aircraft accidents, 1 Jan 1958-31 Dec 1968. Aerospace Med 42:896-898, 1971.

36. Barnum, F.: Spatial disorientation aircraft accidents, 1 Jan 1969-31 Dec 1971: a comparison. Presented at the Annual Scientific Meeting of the Aerospace Medical Association, Las Vegas, NV, 7-10 May 1973.
37. Kellogg, R.S.: Letter report on spatial disorientation incidence statistics. From Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH, to AMD/RDL, 30 Mar 1973.
38. Hixson, W.C., Niven, J.I., and Spezia, E.: Orientation-error accidents in Army aviation aircraft. *In* The Disorientation Incident. AGARD-CP-95-Part I. Benson, A.J. (ed.). NATO/AGARD, Neuilly-sur-Seine, France, 1972.
39. Tyler, P.E., and Furr, P.A.: Disorientation, "fact and fancy." *In* The Disorientation Incident. AGARD-CP-95-Part I. Benson, A.J. (ed.). NATO/AGARD, Neuilly-sur-Seine, France, 1972.
40. Kirkham, W.R., et al.: Spatial disorientation in general aviation accidents. *Aviat Space Environ Med* 49:1080-1086, 1978.
41. McCabe, B.F.: Vestibular suppression in figure skaters. *Trans Amer Acad Ophthal Otolaryngol* 64:264, 1960.
42. Collins, W.E.: Vestibular responses from figure skaters. *Aerospace Med* 37:1098-1104, 1966.
43. Money, K.E., and Malcolm, R.E.: Assessment of films and slides for orientation training of military pilots. *In* Orientation/Disorientation Training of Flying Personnel: A Working Group Report. AGARD-R-625. Benson, A.J. (ed.). NATO/AGARD, Neuilly-sur-Seine, France, 1974.
44. Malcolm, R., et al.: The Malcolm horizon. Presented at the Annual Scientific Meeting of the Aerospace Medical Association, New Orleans, LA, 8-11 May, 1978.
45. Money, K.E.: Theory underlying the Peripheral Vision Horizon Device. DCIEM Technical Communication 82-C-57, Defence and Civil Institute of Environmental Medicine, Downsview, Ontario, Canada, Dec 1982.
46. Wick, R.L.: No flicker vertigo. Letter to the editor. *Business/Commercial Aviation* 51:16, July 1982.
47. Clark, B., Nicholson, M., and Graybiel, A.: Fascination: a cause of pilot error. *J Aviat Med* 24:429-440, 1953.
48. Clark, B., and Graybiel, A.: The Break-off phenomenon--a feeling of separation from the earth experienced by pilots at high altitude. *J Aviat Med* 28:121-126, 1957.

49. Miller, E.F., II, and Graybiel, A.: Comparison of five levels of motion sickness severity as the basis for grading susceptibility. *Aerospace Med* 45:602-609, 1974.
50. Armstrong, H.G.: Chapter 14. Air sickness. *In* *Aerospace Medicine*. Armstrong, H.G. (ed.). Baltimore, The Williams & Wilkins Company, 1961.
51. Benson, A.J.: Chapter 22. Motion sickness. *In* *Aviation Medicine*, Volume I. Physiology and Human Factors. Dhenin, G. (ed.). London, Tri-Med Books Limited, 1978.
52. Kellogg, R.S., Castore, C., and Coward, R.E.: Psychophysiological effects of training in a full-vision simulator. Preprints of the Annual Scientific Meeting of the Aerospace Medical Association, Anaheim, CA, 12-15 May, 1980.
53. Miller, J.W., and Goodson, J.E.: Motion sickness in a helicopter simulator. *Aerospace Med* 31:204-212, 1960.
54. Claremont, C.A.: The psychology of sea sickness. *Psyche* 11:86-90, 1931.
55. Reason, J.T.: Motion sickness adaptation: a neural mismatch model. *J Roy Soc Med* 71:819-829, 1978.
56. Steele, J.E.: Motion sickness and spatial perception--a theoretical study. *In* *Symposium on Motion Sickness with Special Reference to Weightlessness*. AMRL-TDR-63-25, Aerospace Medical Research Laboratory, Wright Patterson AFB, OH, 1963.
57. Treisman, M.: Motion sickness: an evolutionary hypothesis. *Science* 197:493-495, 1977.
58. Money, K.E., and Cheung, B.S.: A mechanism for facilitation of the emetic response to poisons: the basis of motion sickness. Preprints of the Annual Scientific Meeting of the Aerospace Medical Association, Bal Harbour, FL, 10-13 May, 1982.
59. Reason, J.T., and Brand, J.J.: *Motion Sickness*. London, Academic Press, 1975.
60. Ambler, R.K., and Guedry, F.E., Jr.: Reliability and validity of the Brief Vestibular Disorientation Test under 10-rpm and 15-rpm conditions. *Aerospace Med* 42:186-189, 1971.
61. Kennedy, R.S.: Motion sickness questionnaire and field independence scores as predictors of success in naval aviation training. *Aviat Space Environ Med* 46:1349-1352, 1975.

62. Cowings, P.S., and Toscano, W.B.: The relationship of motion sickness susceptibility to learned autonomic control for symptom suppression. Aviat Space Environ Med 53:570-575, 1982.
63. Levy, R.A., Jones, D.R., and Carlson, E.H.: Biofeedback rehabilitation of airsick aircrew. Aviat Space Environ Med 52:118-121, 1981.
64. Graybiel, A., et al.: Human assay of antimotion sickness drugs. Aviat Space Environ Med 46:1107-1118, 1975.
65. Johnson, W.H., Money, K.E., and Graybiel, A.: Airborne testing of three antimotion sickness preparations. Aviat Space Environ Med 47:1214-1216, 1976.

RECOMMENDED READING

- Handbook of Sensory Physiology, Volume II: Somatosensory System. Iggo, A. (ed.). Berlin, Springer-Verlag, 1973.
- Handbook of Sensory Physiology, Volume III/2: Muscle Receptors. Hunt, C.C. (ed.). Berlin, Springer-Verlag, 1974.
- Handbook of Sensory Physiology, Volume VI: Vestibular System. Kornhuber, H.H. (ed.). Berlin, Springer-Verlag, 1974.
- Handbook of Sensory Physiology, Volume VII/3: Central Processing of Visual Information. Jung, R. (ed.). Berlin, Springer-Verlag, 1973.
- Handbook of Sensory Physiology, Volume VIII: Perception. Held, R., Liebowitz, H.W., and Teuber, H.-L. (eds.). Berlin, Springer-Verlag, 1978.
- Wagman, I.H., and Dong, W.K.: Principles of Biodynamics, Volume III: Physiological Mechanisms in the Mammal Underlying Posture, Locomotion, and Orientation in Space. Aeromedical Review 7-75, USAF School of Aerospace Medicine, Brooks AFB, TX, 1975.
- Wilson, V.J., and Jones, G.M.: Mammalian Vestibular Physiology. New York, Plenum Press, 1979.
- Howard, I.P., and Templeton, W.B.: Human Spatial Orientation. London, John Wiley & Sons, 1966.
- Peters, R.A.: Dynamics of the Vestibular System and their Relation to Motion Perception, Spatial Disorientation, and Illusions. NASA CR-1309, National Aeronautics and Space Administration, Washington, DC, 1969.
- Benson, A.J., and Burchard, E.: Spatial Disorientation in Flight--A Handbook for Aircrew. AGARD-AG-170, NATO/AGARD, Neuilly-sur-Seine, France, 1973.
- Money, K.E.: Motion Sickness. Physiological Reviews 50:1-39, 1970.
- Reason, J.R., and Brand, J.J.: Motion Sickness. London, Academic Press, 1975.